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LOCKE
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IMPULSE GENERATOR INSTRUCTIONS & OPERATING PROCEDURES

Impulse Generator Instructions & Operating Procedures

Purpose

This instruction book accumulates pertinent information concerning natural and artificial lightning with the object of aiding laboratory personnel to understand and control the phenomena connected with artificial lightning generators.

The writer wishes to acknowledge the aid of publication written by members of the High Voltage Engineering Laboratory of the General Electric Company, Pittsfield, Massachusetts.

Signed E. M. Dorsey

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IMPULSE GENERATOR INSTRUCTIONS AND OPERATING PROCEDURES

I. General Discussion of Lightning

Since the beginning of recorded time, lightning has been an occurrance of fear and mystery. Very little about it was known until Benjamin Franklin demonstrated that lightning was an electrical phenomenon.

With the coming of transmission lines it became more important to determine just what lightning was. At a very early time in the history of transmission lines it was noted that lightning was one of the major technical problems that had to be overcome. Since transmission lines are constructed at some height above the surrounding terrain, they are usually the most prominent object of that particular locality and therefore most susceptable to being struck by lightning. When a transmission line is struck by lightning serious damage occurs to line insulation, sub-stations, and generating equipment creating much expense and interruption of the continuity of the service that is supplied by these lines.

Over the years transmission line engineers and high voltage experts have managed to develop many types of protective devices. These protective devices such as; lightning arrestors, expulsion tubes, overhead ground wires and fast relaying techniques, have led to the term "lightning proof" transmission lines .

II. Lightning Investigations

The engineers' first studies were confined to the effect of lightning, and it was found that lightning strokes are characterized by a relatively high current flowing for a short interval of time. This means that when the transmission line is struck by lightning this fast surge of current through the impedance of the line produces a voltage drop between the line and ground. This voltage wave immediately starts to travel in both directions along the transmission line subjecting the line insulation and equipment to relatively high voltage stresses. These "traveling waves" may also be produced by induced effects from nearby strokes which do not actually contact the transmission line. By actual field investigation it has been found that the shape of these high voltage waves varies considerably.

III. Actual Lightning Waves

Wave fronts have been found to range from one to 90 microseconds to crest and from 1 to 200 microseconds duration on the tail. An analysis of these data by Bewley indicated that the majority of the fronts were from 1 to 5 microseconds and that the duration of the tail was from 10 to 40 microseconds. From this data a standard test wave described as a $1\frac{1}{2} \times 40$ microsecond wave was established by the industry so that testing could be conducted on a common basis. (Methods of defining wave shape will be explained later).

From the above discussion it becomes apparent that the $1\frac{1}{2} \times 40$ microsecond wave is not an actual lightning stroke but is a standardized voltage wave which is perhaps a little more severe than most actual lightning strokes.

In determining what magnitudes of voltage might be found to exist on transmission lines during lightning strokes it was realized that the high rate of change of current must be determined. Field investigation has shown that the current in lightning strokes may be as low as 1000 or as high as 100,000 amperes and that the rate of change of current may be as high as 40,000 amperes per microsecond, with a probable average of 4500 amperes per microsecond. From this data it is estimated that lightning voltages will range between 1 KV and 10,000 KV depending upon the impedance of the line struck.

Fortunately this voltage wave can be "chopped off" by the line insulation and only voltages having a magnitude of a little more than the critical flashover voltage of the line would reach the transformers and sub-station or generating station equipment. In addition the natural attenuation of a transmission line decreases the magnitude and lessens the severity of a stroke as it approaches sub-stations or generating equipment.

IV. Types of Lightning Waves

Since lightning waves are altered by the line insulation, expensive equipment may be subjected to three different types of waves. Waves having magnitudes slightly higher than the critical flashover value will be "chopped off" at or beyond the crest and the wave reaching the apparatus will be a "chopped wave". Magnitudes greatly in excess of the critical flashover value will be "chopped off" on the crest or before the crest. This wave when reaching the apparatus will be a "steep front" wave provided that the point of lightning stroke contact is not so distant from the apparatus as to be greatly attenuated by the time it reaches the apparatus. The other wave is the full wave in which the magnitude of the lightning voltage is less than the critical flashover of the line insulation. Therefore in laboratory tests, we attempt to duplicate these three different types of waves.

V. Wave Shape Defined

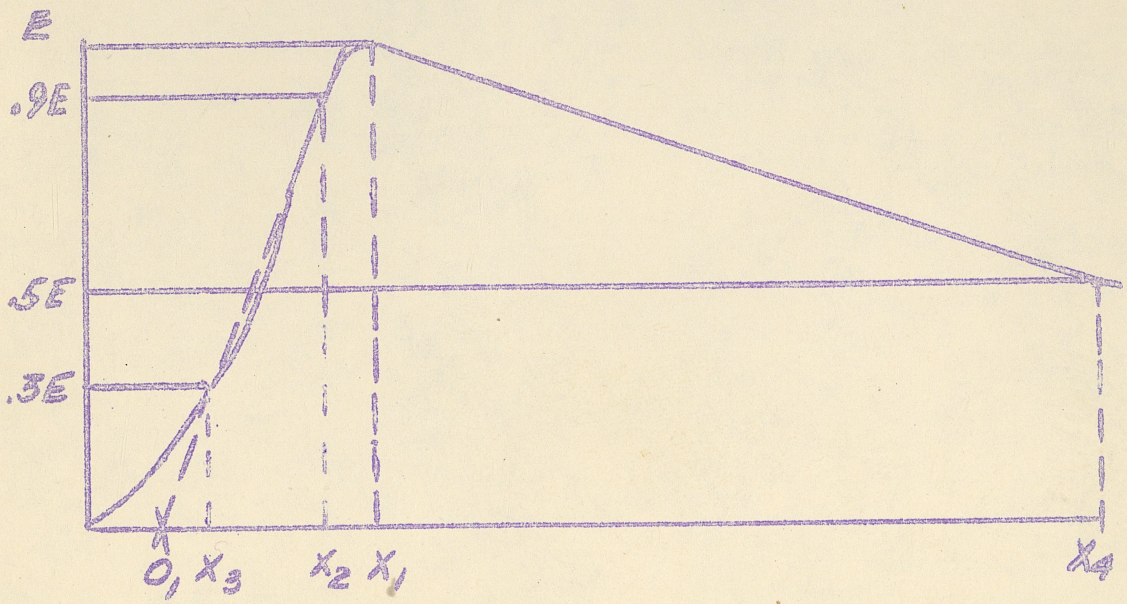
Fig. I. illustrates a typical full wave. Such waves are specified as $T_1 x T_2$ where T_1 and T_2 are the intervals O_1X_1 and O_1X_4 respectively. For practical reasons the virtual zero time is established at O_1 and is determined by the intersection of a line drawn through the .3E and .9E points on the front of the wave, with the zero axis. X_1 is the time at which the crest occurs. The time interval $O_1X_1 = T_1$ and defines the wave front.

For convenience when the crest is not clear the time of the wave front can be considered as two times the actual time interval between the .3E point and the .9E point or $T_1 = 2 (X_2 - X_3)$.

If there are spurious oscillations on the wave front which can't be dampened out, the .3E and .9E points should be established on an average curve sketched through the oscillations.

In Fig. I. the point X_4 is established by determining the time at which .5E occurs in the tail of the wave. The time interval $O_1 X_4 = T_2$ defines the tail of the wave.

Fig. I. Wave Shape



VI. Testing Waves

As explained in the previous section, laboratory impulse testing waves are an attempt to duplicate the different types of waves which might actually occur on apparatus due to the occurrance of a lightning stroke contacting a transmission line. Figure I illustrates these three different waves. Referring to Figure I wave #1 is a $1\frac{1}{2} \times 40$ microsecond full wave the amplitude of which is such that the wave would not cause flashover of the line insulation or apparatus bushings used with the particular voltage class of the apparatus under consideration. Such voltage amplitudes have been standardized for all common voltage classes. This means that the apparatus would have to have internal insulation with sufficient strength to withstand this full wave. Wave #2 of Figure I is an example of "chopped wave", the amplitude of which is approximately 15% higher than the full wave. In general this voltage would cause flashover of the line insulation or apparatus bushing thus producing a "chopped off" effect on the tail. On apparatus this "chopped off" effect may be produced by gaps or the apparatus bushing. The third wave, the "steep front" wave, gives rise to a somewhat special test. This is the steep front wave shown by wave curve #3 of Figure II. Such a wave is roughly 60% higher than the full wave but of very short duration. This type of wave is only experienced on transmission lines which do not provide lightning arrestors or other protective devices. When these operating practices are adhered to, voltage waves much in excess of the critical impulse flashover value of the line insulation, when occurring at or near the apparatus, will produce the steep front wave even if spilled gaps are used. This type of wave is a much more severe wave than either of the other two types. Therefore, this operating procedure in which lightning protective devices are not used, can only be justified on an economic basis where continuity of service is not of prime importance.

Figure II

Types of Lightning Waves

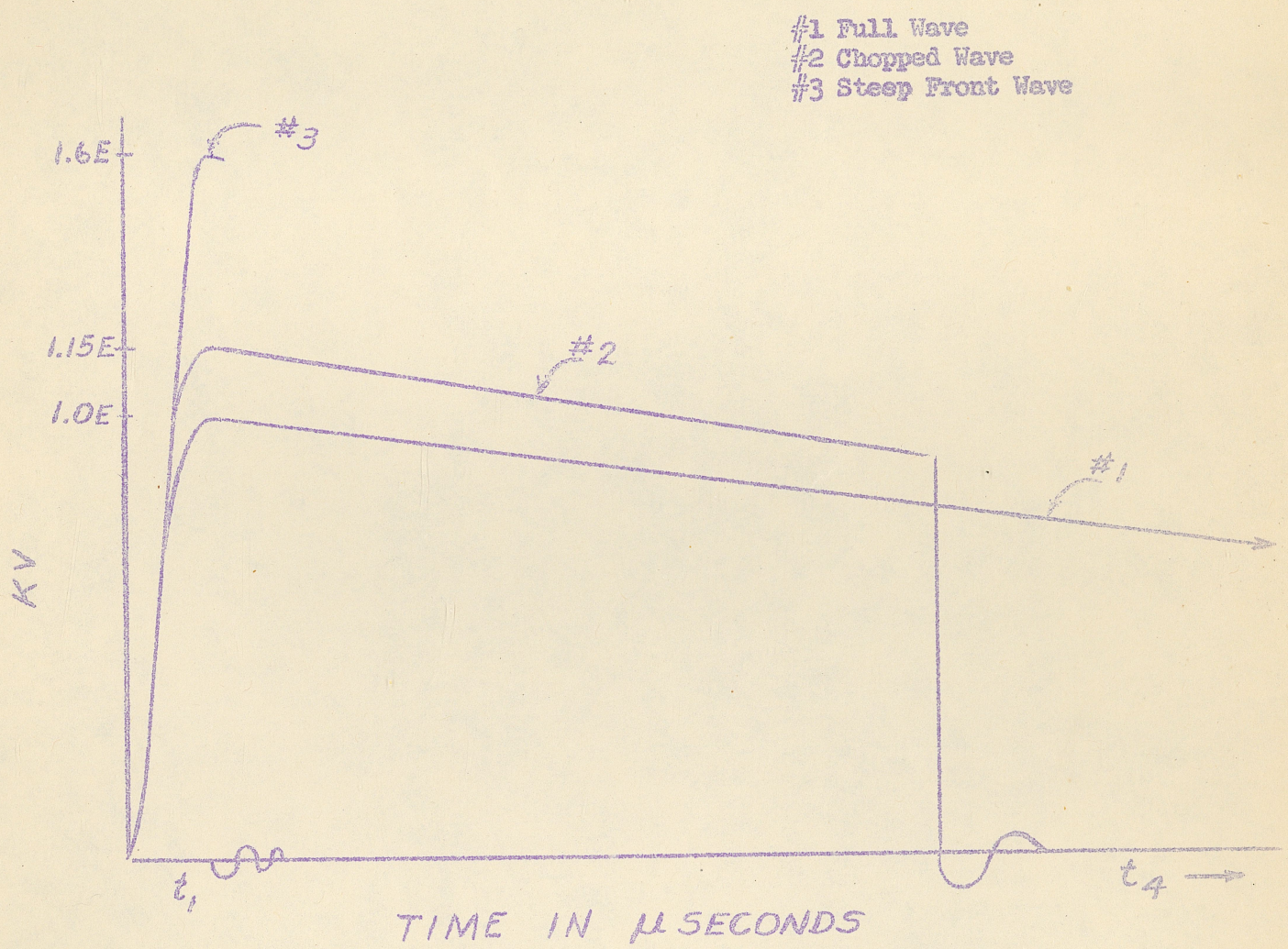
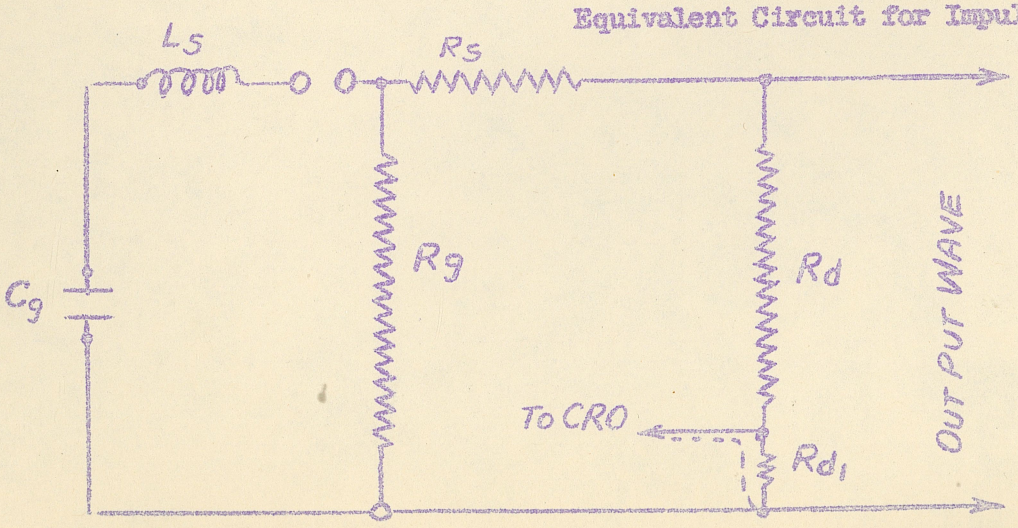


Figure III

Equivalent Circuit for Impulse Generator



VII. Artifical Lightning Circuits

The leboratory lightning generators which made possible the production of an artifical lightning stroke are essentially a discharge of a capacitor. Most generators in use today are modified Marx's circuit generators. By using a series resistance between the capacitance of the generator and the impedance of the apparatus under test and by using shunting resistors the wave shape applied to the test piece may be controlled and made to conform to the commercially standardized $1\frac{1}{2} \times 40$ microsecond wave. A typical equivalent circuit for an impulse generator is illustrated in Figure III. The impulse generator itself is represented by the capacitance (C_g) the inductance (L_g) and the isolating gap (g). In the actual circuits C_g is made up of many capacitors connected in series by many gaps. L_g is also distributed among the capacitors. The remainder of the equivalent circuit is to shape the output of the generator into the standard $1\frac{1}{2} \times 40$ wave. The resistances R_d and $R_{d'}$ are resistance voltage dividers whose function is to produce a reduction in the voltage magnitude so that the impulse wave can be recorded by a cathode ray oscillograph. R_g is a shunting resistor which aids in the control of the tail of the wave.

After the impulse generator capacitance (C_g) has been charged by a DC voltage to some predetermined value, the series gap (G) is made to spark over, thus causing the impulse generator to discharge into the rest of the circuit. The output voltage (the voltage across the test specimen, load capacitor, and the voltage divider) rises until the load capacitance and the impulse generator capacitance are essentially at the same voltage. This is the crest voltage and the part of the wave up to this point is called the wave front. Beyond the crest the impulse generator capacitance C_g and the load capacitance C_L act in parallel and discharge through the series resistance R_s and voltage divider resistance R_d and wave tail shaping resistance R_g. This portion of the wave is called the wave tail.

VIII. Calculations for Wave Front

The wave front is determined by the RC time constant of the load capacitance (C_L) and the series resistence (R_s), the self inductance (L_s), and the impulse generator capacitance (C_g) (Appendix I gives the theoretical calculation for wave fronts and wave tails. From this it can be shown that, provided the series resistance (R_s) is sufficiently large to prevent oscillation on the crest of the wave, the equation for the time to crest is approximately 2.5 times the RC constant of the output circuit. Where C is the effective series capacitance of the generator capacitance (C_g) and the load capacitance (C_L) or where C is equal to $C = \frac{C_L C_g}{C_L + C_g}$. In other words, the wave front time in microseconds equals 2.5 times R_s times C. The minimum value of R_s can be determined from the equation for critical dampening or R_s minimum is $2\sqrt{L_s/C}$. In actual practice it is found that the load capacitance (C_L) is only about 1% to 10% of the generator capacitance (C_g) therefore the equation for wave front may be reduced to time of wave front in micro-seconds (t) is equal to 2.5 R_s C_L in microfarads. The constant 2.5 is theoretically obtained by assuming that the voltage built up across (C_g) the generator capacitance (C_g) remains constant during the time to the crest value. Obviously this is an error since the generator capacitance C_g starts to discharge the instant that the gap (G) breaks down. Since the constant 2.5 is dependent upon a discharge rate of C_g it is obvious that the length of the tail will have an effect upon this constant.

IX. Calculations for Wave Tail

As soon as the load capacitor reaches crest value, the generator capacitor (C_g) and the load capacitor (C_L) immediately start to discharge through the effective resistance shunting them. In the type of wave shaping circuit used in the Locke High Voltage Laboratory in which an R_d, R_s, and R_g are used the effective shunting resistance is considered to be the parallel combination of R_d plus R_s and R_g. Since C_g is much greater than C_L the discharge current is considered to split at the junction of R_s and R_g. Therefore, the equation for effective shunting resistance is $R = \frac{R_g (R_s + R_d)}{R_g + R_s + R_g}$. From Appendix A we find the equation for time of wave tail (t_2) is $t_2 = 0.7R (C_g + C_L)$.

X. Voltage Regulation

In operating an impulse generator it is desirous to know the approximate regulation which will occur in the output circuit. Two types of regulations take place. One is the effective ratio of the capacitance of the generator and the capacitance of the load circuit, the other the voltage divider effect of the combination between R_s and R_d. The generator output E_c in terms of the capacitance regulation is $E_c = \frac{E_o C_g}{C_g + C_L}$. Where E_o is equal to the charging voltage of the generator times the number of capacitors and E_c is the generator voltage (E_o) regulated by capacitor effects.

In considering the resistive regulation (E_r), E_r would equal $R_d E_o$. Therefore, in terms of both $\frac{E_r}{E_o}$ and $\frac{E_c}{E_o}$ the output regulation $\frac{E_r}{E_o} = \frac{C_g}{C_g + C_L} \frac{R_d}{R_s + R_d}$

This equation is not precise, however, for most modern generators using the $1\frac{1}{2} \times 40$ microsecond impulse wave it gives a very close approximation. The error is due to neglecting the series inductance of the circuit which causes additional voltage rise at the crest.

XI. The Locke Impulse Generator Circuit

The 3,000,000 volt impulse generator now in the High Voltage Laboratory of the Locke Department, G.E. is indicated schematically in Figure IV. The generator consists of the following main parts. Induction regulator, rectifier, capacitor bank, wave shaping resistors, and a trip unit.

In normal operation power is supplied to the induction regulator which varies the input voltage to the rectifier transformer. The DC output which is placed across C_1 and C_2 is obtained from a voltage doubler type of circuit using two kenetron tubes (V_1 and V_2). The operation of this rectifier set is as follows: At any given positive half cycle of the excitation voltage, V_2 will conduct through the capacitor C_2 and the transformer by means of the charging resistors R_{co} and R_{c1}. During the negative half cycle of the excitation voltage V_1 will conduct placing a charge across C_1 by means of the rectifier transformer and the charging resistors R_{co} and R_{c2}. In this manner during the charging up period a positive charge will be placed on one side of each group of capacitors and the negative charge will be placed upon the other.

The charging resistors R_{c1}, R_{c2} --- R_{cn} allow the capacitors to charge on a relatively long time constant but issolate them during the discharge of the generator; Caution: Inasmuch as the capacitors C_1 and C_2, etc. are individually rated at 75 KV DC, the lower side voltage of the rectifier transformer input should be limited to approximately 360 volts.

If the trip gap T_g were now to be short-circuited, the generator would fire in the following manner. When T_g closes, point (1) would be reduced from some positive potential to a ground potential. This pulse would travel through C_2 and C_1. Point (2) would now have twice the negative potential then what it had while the generator was charging. This would increase the voltage gradient across G_1 causing it to break down. It then follows that the voltage at point (2) would be placed at point (3) causing a further reduction in voltage at point (4), causing G_2 to break down and so on. In this manner, through its internal gaps, the voltages across the individual capacitors of the generator would be added up and discharged through the final gap into the

wave shaping circuit consisting of R_s, R_g, R_d, R_{d1}, and C_L placing the output voltage across the test specimen.

In actual practice the gap T_g is short-circuited by means of the trip unit. The trip unit is essentially another small impulse generator which has an output voltage of approximately 62-1/2 KV. One end of this small trip unit is grounded through the tube V_3 which is a hydrogen filled thyraton. The 62-1/2 KV pulse is placed upon the gap (T_g) which upsets its gradient sufficiently to break down the center gaps. The grid of V_3 is triggered by a pulse from the time delay circuit of the CRO. This rather complicated firing mechanism is essential in that reliable control of the instant the generator fires is desirous since that time must be synchronized with the start of the horizontal sweep on the CRO.

A positive output voltage on the impulse generator may be obtained by changing the output connections of V_1 and V_2 as shown by the dotted lines in the schematic diagram of Figure IV.

FIG. II

IMPULSE GENERATOR SCHEMATIC DIAGRAM

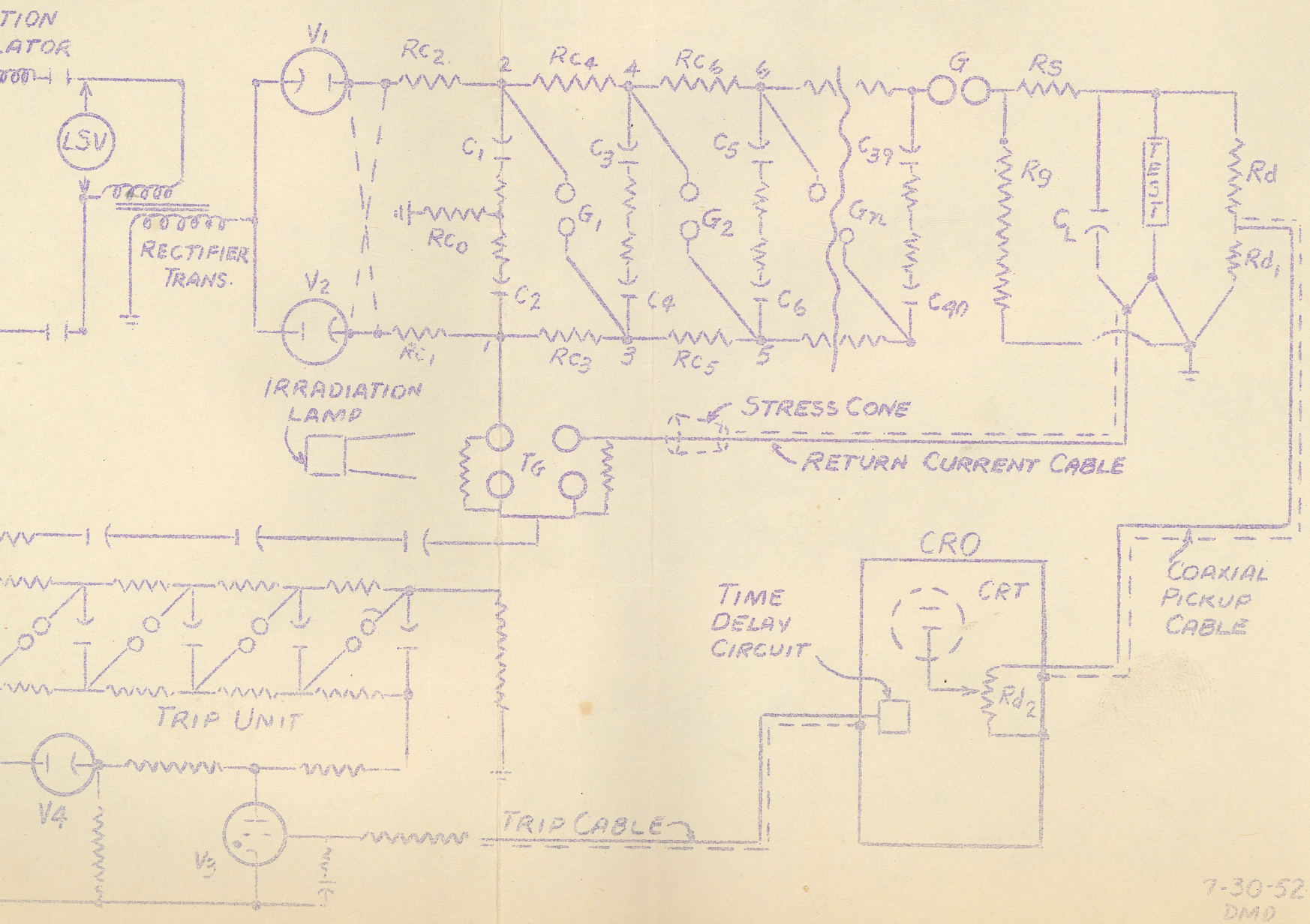


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FIG. 12.

IMPULSE GENERATOR SCHEMATIC DIAGRAM

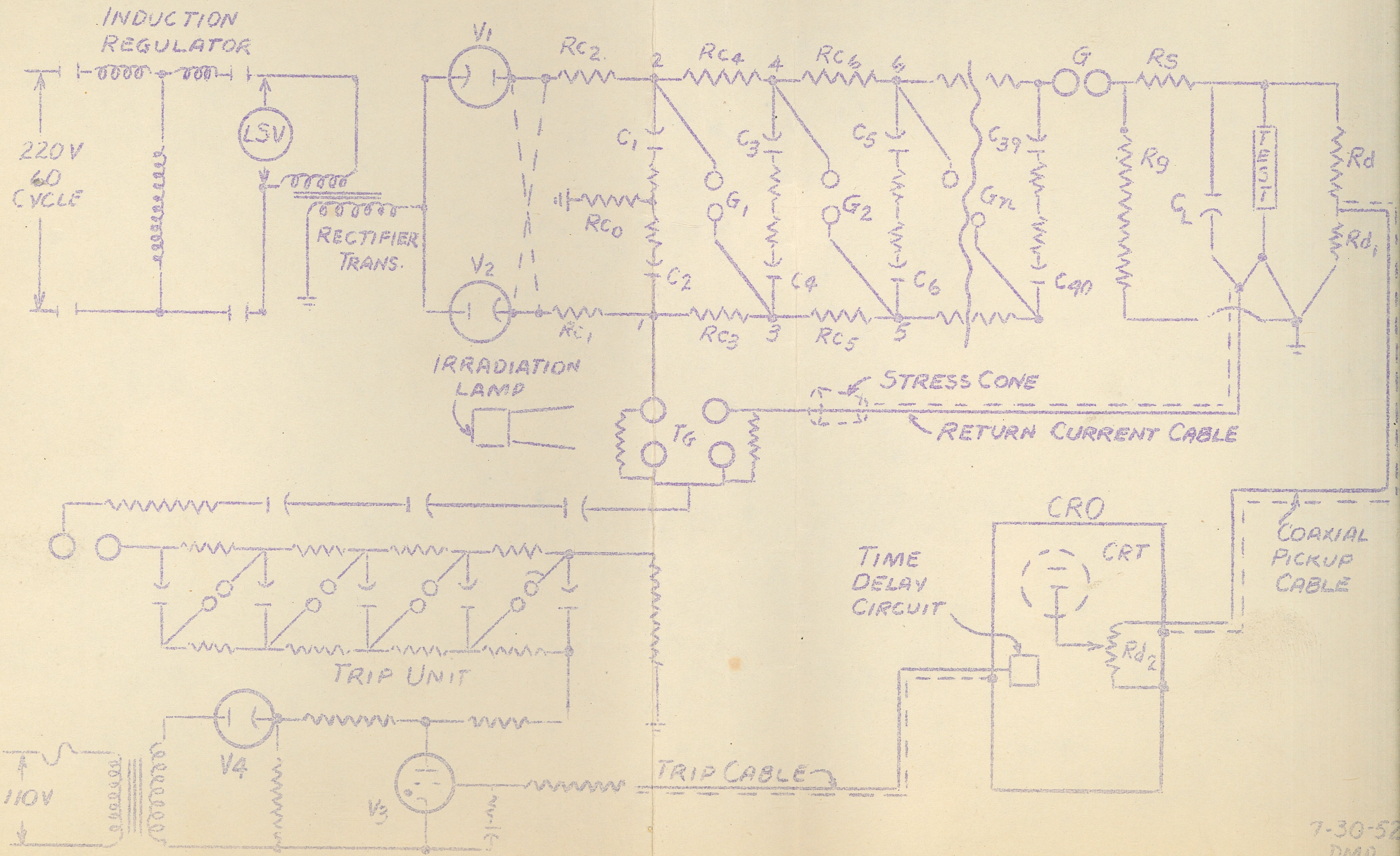

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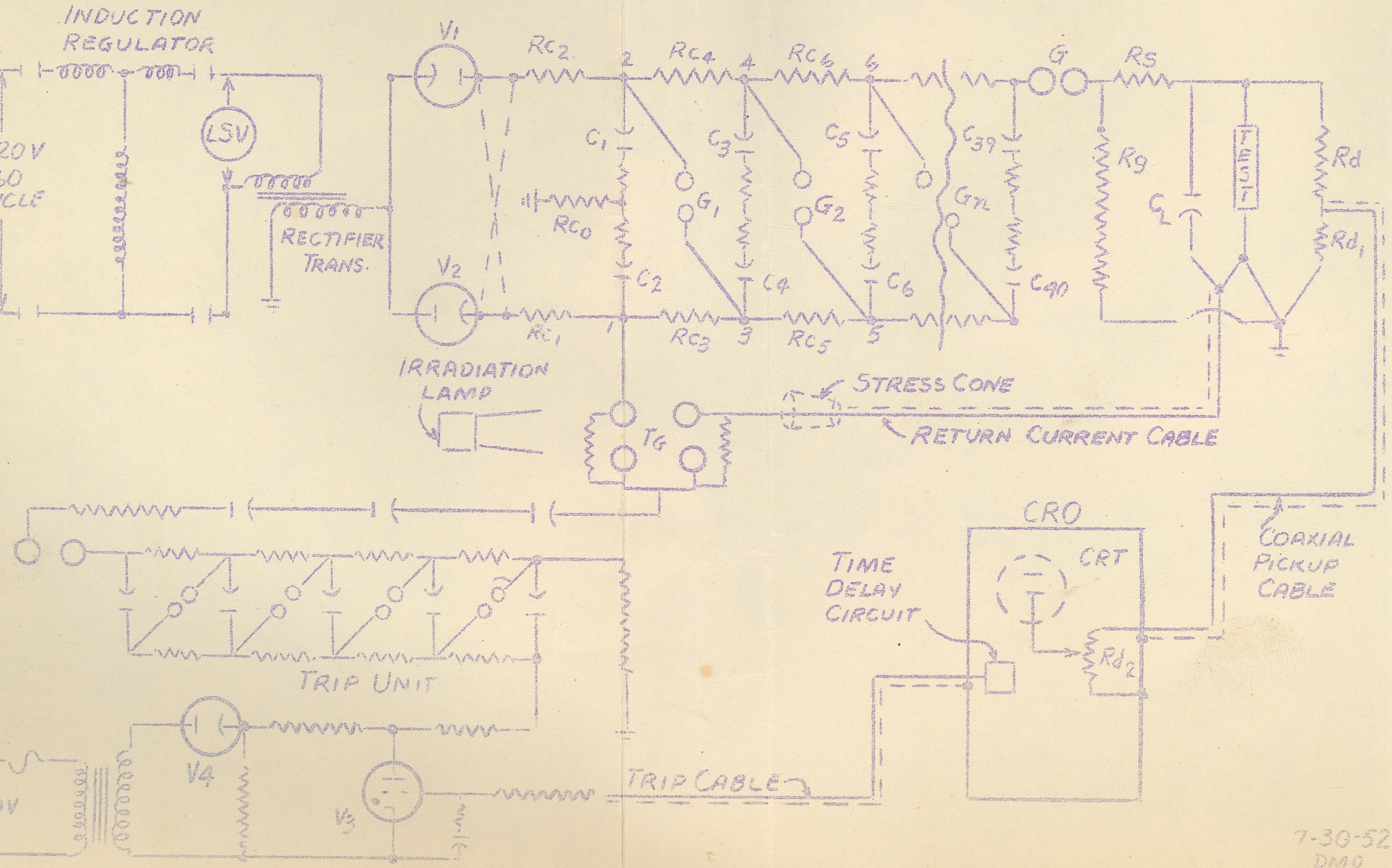
FIG. II.

IMPULSE GENERATOR SCHEMATIC DIAGRAM



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XII. Voltage Dividers

Since there is no known method of accurately measuring high voltages directly, some type of voltage divider must be used. Several types are in use today. These are the capacitance dividers, the compensated dividers and the resistance dividers. Since the main purpose of a divider is to accurately reproduce a voltage shape in miniature the magnitude being reduced by a value equivalent to the voltage divider ratio, extreme caution must be observed in obtaining this ratio. The capacitance divider is greatly effected by stray capacitance and therefore must be calibrated by the use of a resistance divider. The compensated divider, while found to be experimentally very effective in that it attenuates all frequency to the same degree, is not too practical because it becomes extremely large at higher voltages. The resistance divider is favored by most laboratories within the G. E. Company as it is the most flexible and when used properly gives the best result. The resistance voltage divider must be kept well away from the influence of the generator field otherwise it would be a partially compensated divider. The RC time constant of the divider must be kept to a small enough value so that the waves placed across them are not distorted on the output end. The resistors used in this divider must be as highly non-inductive as possible. Every attempt must be made to uniformly grade the applied voltage across these resistors, and again, the voltage divider ratio must be stable and capable of being accurately determined. All connections must be tight because any spurious discharges would distort the wave shape and change the voltage gradient on the resistors creating a transient change in divider radio. The resistance values of the component parts of the voltage divider must be very accurately determined. This measured resistance value must be checked against the calculated resistance inasmuch as the non-inductively wound resistors might have one side open giving twice the rated resistance across this particular card. When the high voltage is impressed across this card, the small break will spark over giving the rated value of resistance, therefore, the measured resistance value would not be the true value under operating conditions.

The voltage divider ratio is equal to VDR = $\frac{R_d}{R_d + R_o}$ where R_o is equal to the parallel effective resistance of R_1 and the terminating impedance R_2 of the co-axial pick-up cable. In selecting the proper size of voltage divider, two things must be considered. The minimum time to be measured and the maximum voltage to be impressed across the divider. The maximum voltage per resistor card should not exceed 50 KV and the total value of the resistance divider should correspond with the values as indicated in AIEE Standards No. 4, Revised, Paragraph 4-163.

XIII. Cathode Ray Oscillograph

The cathode ray oscillograph is an instrument containing various DC power supplies, timing waves, sweep circuits and other associated control equipment, all built to operate an evacuated tube containing an electron beam emitter (cathode) focusing electrodes, deflection plates and accelerating plates (anodes).

If a voltage which varies linearly with time is suddenly impressed upon the horizontal deflection plates of the CRT and the voltage wave to be measured is impressed upon the vertical deflection plates, the electron beam will be deflected proportionally, and thus the time-voltage relationship of the wave to be measured will be plotted when these deflected electrons impinge upon a florescent screen. Photographic prints may be taken of this plot, securing a permanent record of the wave.

By means of the timing waves, DC calibration voltages, and the voltage divider ratios, the exact wave shape and magnitude may be determined.

In most testing the accuracy of the voltage magnitude as indicated by the CRO and the voltage divider ratio must be checked against the magnitude of the same voltage wave as measured by standard sphere gaps. They must not differ from each other by more than 5%. Methods of making these checks are outlined in AIEE Standards No. 4, Revised, Paragraph 4-166.

When testing and using voltages in excess of 1400 KV, the oscillograph must be solely relied upon because as sphere gaps are inaccurate in that range. Therefore, the fact that the accuracy of the CRO and the voltage divider must be maintained is emphasized.

It is highly important that the pick up cable from the voltage divider to the CRO be terminated by a value of resistance equivalent to the surge impedance of the test pick-up cable. This terminating impedance is imperative at the CRO end of the pick-up cable but is not necessary at the voltage divider end.

XIV. How to Select The Proper Standard Generator Circuit

Determine the range of voltage at which tests will be desired. Determine minimum time to flashover which will be expected. Select a standard size generator compatible with the above conditions. Standard generator curves are given in the Appendix. They have been set up so that a wide variety of the above conditions may be obtained. The particular curves are a calibration of lower side voltage versus sphere gap spark overs for $1\frac{1}{2} \times 40$ waves. The calibrations hold only as long as the exact circuitry is duplicated as given on the curve sheet. Any variation in the circuitry (Except changes in R_{d1}) constitutes a non-standard set-up and a new calibration curve must be obtained.

XV. Non-Standard Generator Circuits

When the use of a standard size generator is not feasible other types of generators may be set up by paralleling the generator capacitors, splitting up the generator, inserting internal resistance, making variations in wave shaping resistors or load capacitor.

The following rules should be strictly adhered to when setting up non-standard generators.

(a) Always maintain adequate charging resistance in the generator between all banks of capacitors.

(b) Grade all voltages as uniformly as possible. This is imperative in the case of the voltage divider as non-uniform gradients will affect the divider ratio.

(c) Do not exceed 75 KV crest per resistor card. (50 KV per card on voltage divider).

(d) Keep the inductance as low as possible by avoiding the use of long lead lengths or small diameter wires.

(e) Appearance of "over shoot" on the crest of a full wave indicates that excessive inductance is present in the circuit. This will lead to an error in the calibration.

(f) Keep the return currents separate from the grounding circuits. The high return currents if introduced in any major proportion into the ground circuit, will create $\frac{L di}{dt}$ drop in these ground leads and will, therefore, raise, above actual ground, points which should be kept at ground.

(g) Maintain generator sphere gaps in as clean a condition as possible.

(h) Metal parts of the generator should always be tied in with the rest of the circuit. Floating metal parts draw capacitive currents which will cause spurious spark-overs which have the effect of distorting the output wave. All spurious spark-overs must be avoided.

Do not exceed 2500 volts across R_{dl}.

One side of the test specimen and the ground side of R_{dl} must be kept at ground potential at all times.

XVI. Operating Procedure

An impulse generator is an expensive and highly specialized piece of equipment. In its design optimum mechanical strength has been sacrificed to enhance its electrical strength. For this reason it would not be subjected to excessive mechanical stresses of any type.

After the proper type of generator has been set up the following procedures should be followed in starting up the generator.

1. Check entire circuit for proper connections and tightness of connectors.
2. Select the proper polarity.
3. Remove both grounding and shorting straps on the condensers.
4. Throw in safety disconnect switch located on left side of the control panel.
   (a) Green light comes on indicating power available.
   (b) Green light in gate circuit signal light comes on if safety circuit selector switch located by the stairs is in the proper position.
5. Throw filament switch to start position and hold for 10 seconds then quickly change to run position.
   (a) Adjust filament voltage to red line by using fine control knob.
   (b) When the rectifier filament switch is placed in the run position, the filament on the trip unit power supply chaise are also turned on. Since a hydrogen filled thyration is used for tripping, a 5 minute time delay locks out the high voltage to the thyration to allow it to reach the proper operating temperature.
6. Turn on 110 volt switch to the oscillograph.
   (a) Be sure that the back oscillograph door is closed. The back door is interlocked with the high voltage power supply of the oscillograph.
   (b) The oscillograph contains a thermal time delay to allow it to heat up.

7. Turn on the 300V, 900V and 25 KV power supplies to the oscillograph.

   (a) Observe the CRO tube while turning on the 25 KV power supply since the tube would burn up if a failure had occurred in the 900 volt power supply.

8. Adjust the oscillograph to the proper sweep speed, timing wave, DC calibration, focus, intensity, bias, and the camera to the proper aperature opening.

   (a) Excessive intensity should be avoided in that it clouds films and shortens the life of the CRT.

   (b) Use the green CRO button for tripping the CRO while making these adjustments. This button does not trip the impulse generator.

9. Close all interlock gate circuits.

   (a) A large green light located on the left-hand side of the control panel lights when all gates are properly connected and closed.

10. With the volt meter selector switch on the highest range, turn the control switch to "regulator" position.

   (a) Red light over regulator position goes on indicating that regulator is energized. Observe voltage on volt meter.

11. Check the operation of the gate circuits by opening one of the gates. The regulator contactor should trip out.

   (a) Sign safety record book to indicate the above checks and state condition of circuits.

12. Throw regulator in and adjust to the approximate lower side voltage (LSV) as determined by the standard curve of LSV verses KV for the particular generator which has been set up or from some other appropriate calibration curve.

13. Adjust the gap spacing to correspond with the LSV as per posted curve.

Note: This gap spacing is approximate and should be used only as a guide in making initial settings.

14. With the "trip-no-trip" switch in the "no-trip" position, throw the control switch to the rectifier position. This will perform the following operations;

(a) Remove the ground from the output of the rectifier set.

(b) Close the contactors between the regulator and rectifier.

(c) Turn on the high voltage to the trip unit.

(d) Switch the gate signal lights from green to red.

(e) Start the charging time timer.

Caution: If excessive regulation of the LSV is indicated, trip the circuit immediately since a short is probably on the circuit. If rapid firing of the generator occurs, the gaps are probably too close together and must be immediately opened up. Continued rapid firing will blow the 1.25 amp fuse in the trip unit power supply.

15. When the charging time buzzer signals sounds and with the CRO selector switch on the VD position, push the red surge button on the CRO. This will cause the following sequence of operation. The CRO button picks up a relay on the time delay circuit which fires a thyration which sends out two pulses. One going through a variable time delay circuit to the trip unit, the other goes through a 1 microsecond time delay cable and starts the sweep. The one going to the trip unit will short out the thyration causing the trip generator to fire and thus the main generator to fire. If all connections and adjustments are correct, you will observe the output wave of the generator on the CRO scope. If it is desired to take a picture of this wave, prior to pushing the surge button, the switch on the top of the camera holder must be closed.

16. If CRO trace is not in the center of the tube, correct by using the timing control, or bias control. If trace does not appear at all, the main gaps in the generator may be spaced too far apart in which case they should be closed down by use of the gap control mechanism.

17. The generator may be shut down automatically at the end of any one firing by placing the "trip-no-trip" toggle switch in the trip position. This switch has to be reversed to the "no-trip" position prior to starting up again.

Caution: Prior to doing any work in the impulse generator area or immediately upon entering the impulse generator area, all dangerous parts of the impulse generator must be grounded and shorted. These are (1) Normal grounding safety switches mounted on output of rectifier. (2) Grounding and shorting strap on crank mechanism for both sides of the generator. (3) Test specimens having high capacitance.

18. When re-adjusting the LSV to a different level, it should be remembered that the generator will charge to approximately the highest LSV applied, not necessarily to the final point of adjustment. For this reason it would be good practice to turn off the rectifier to adjust the LSV.

19. Data should consist of the following items; specimen information, generator set-up (if standard, the curve number may be referred to), wet and dry bulb readings, barometer reading, polarity of the generator, lower side voltage (LSV), timing wave, frequency, sweep speed, DC calibration voltage and polarity, number of the picture taken, what type of flashover occurred. For most of the testing done in the Locke Laboratory, it has been found expedient to place both timing wave and a DC calibration voltage on every exposure.

XVII. Trouble "Shooting"

Symptom #1: Regulator will not trip in.

(a) Check all gate circuits.

(b) Check position of safety circuit selector switch.

(c) Check fuses to pick up coil.

(d) Check filament switch, should be in run position.

Symptom #2: No high voltage on trip unit.

(1) Check 1.25 amp fuse. Fuse probably blew because gaps on trip generator were too close.

(2) Check 1B3 tube for proper operation.

Symptom #3: Lack of control over generator firing. The four electrode gap, although irradiated, is irregular in its performance with respect to changes in humidity. In addition, small amounts of dirt or dust will greatly change their flashover characteristics Since a large majority of the variable time delay in firing a generator is located in these gaps, it is essential that they be clean and spaced properly. The ground side set of gaps should be spaced closer than the high side set of gaps. Prior to re-adjusting the spacing of the gaps, it should be determined whether or not the trip unit itself is operating properly. This may be done by turning the rectifier on but reducing the ISV to zero and then attempting to trip the trip unit. If the trip unit is operating properly, you should then look to the relative spacing between the large internal gaps of the generator and the four electrode gap. If the generator seems to be firing at a spacing which is quite a bit higher than that indicated on the ISV versus gap spacing curve the four electrode gaps are probably set too close. On the other hand, if it is impossible to obtain the correct timing so that the impulse can be observed on the screen of the CRO tubes, it is highly probable that there is too much delay in this gap because it is too far apart. With experience these gaps should be relatively easy to maintain in proper operating condition.

Symptom #4: No trace on tube.

1. Lack of sufficient intensity or focus.

2. Failure of 25 KV accelerating voltage. Check fuse. Failure of sweep circuit to

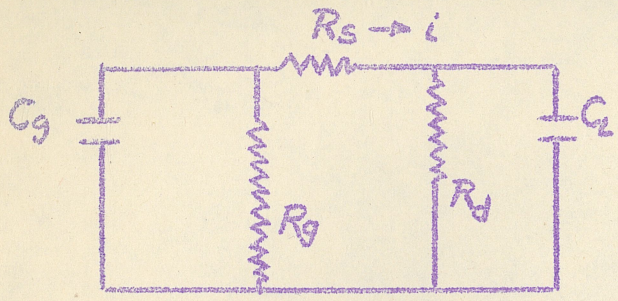
produce a CRO grid trip. Check sweep circuit operation by checking current jacks in chassis.

Symptom #5: Irratic firing of the generator.

1. Clean and re-adjust all gaps.
2. Listen for capacitor breakdowns.
3. Trip unit gaps too close. Ionizing wisker too close.

Symptom #6: Poor timing between start of sweep and firing of generator. This is also probably poor adjustment of gaps and is more noticeable on the shorter sweep speeds. Check irradiation for proper operation. Check thyrations of time delay circuit.

DERIVATION OF AN APPROXIMATE FORMULA FOR FRONT OF WAVE CALCULATION.



C_L = Load Capacitance

C_g = Generator Capacitance

R_s = Series Discharge Resistance

R_d = Voltage Divider Resistance

Figure I

Discussion of Circuit

Since C_g is much greater than C_L and R_d is much greater than R_g which is much greater than R_s, and since the time for the voltage across C_L to reach crest is very small compared to the total discharge time of C_g, the circuit can be assumed to take the form of Figure II. Inductance is very small and so is neglected.

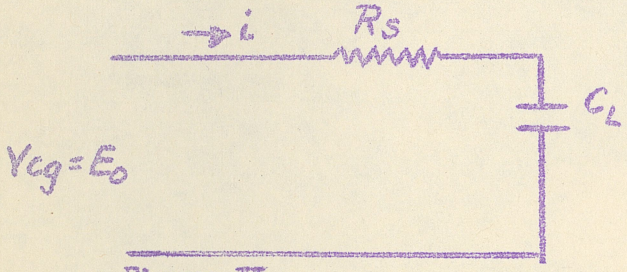


Figure II

Here the load capacitance is charged from a constant potential ($Vc_g = E_o$) source through the dampening and charging resistor (R_s). This E_o is also assumed to be equal to the crest voltage that would have been obtained in Figure I.

In other words the discharging effect of R_g and R_d is neglected. Keeping Figure II and the assumption above in mind, the voltage appearing across C_L V_ys time would appear as in Figure III.

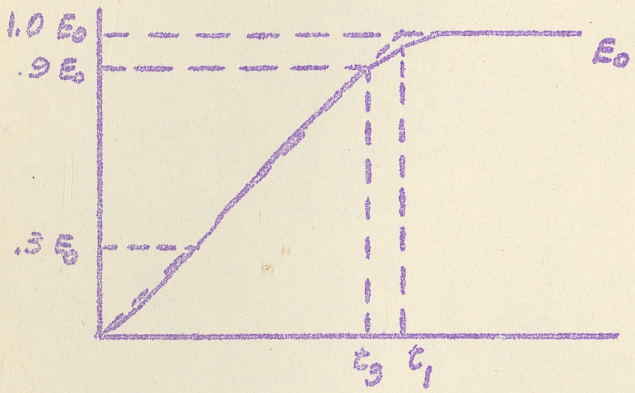


Figure III

Derivation of Wave Front Formula

At any time (t_n) the sum of the voltages in the circuit of Figure II is equal to zero.

$1/C_L \int idt + iR_s - E_o = 0$ Equation 1a

Differentiate Equation 1a with respect to t:

$i\ 1/C_L + R_s\ di/dt = 0$, or $i + R_s C_L\ di/dt = 0$ Equation 2a

This has the classical solution which takes the form.

$i = e^{mt}$ Equation 3a

$di/dt = me^{mt}$ Equation 3.1a

Substitute Equation 3a and Equation 3.1a in Equation 2a:

$e^{mt} + R_s C_L me^{mt} = 0$ or $1 + R_s C_L m = 0$

Solve for m:

$m = \frac{-1}{R_s C_L}$ Equation 4a

Substitute Equation 4a in Equation 3a and remembering that for every value of n there is a constant K to be determined from the limiting conditions:

$$i = Ke^{-t/R_sC_L} \qquad \text{Equation 5a}$$

at time $t_n = o$ from Equation 1a, $i = E/R_s$

So from Equation 5a at time = o, $i = K = E/R_s$

Therefore at any time t_n

$$i = E/R_s\, e^{-t_n/R_sC_L} \qquad \text{Equation 6a}$$

The Equation for the voltage (VC_L) across C_L at any time from Equation 1a is; $Vc_L = 1/C_L \int idt = E_o - iR_s$ Equation 7a

Substitute Equation 6a in Equation 7a

$$Vc_L = E_o - E_o/R_s\, R_s e^{-t_n/R_sC_L} = E_o\,(1-e^{-t_n/R_sC_L}) \qquad \text{Equation 8a}$$

Since the AIEE standard #4 defines the virtual zero of the wave as the line through the .3 E_o and .9 E_o points and assuming that t_1 coincides with the time of crest equals E_o, we can solve for t_3 at .9 E_o, and t_1 at E_o will be proportional.

At .9 E_o Equation 8a reads, $Vc_L = .9\,Eo_o = Eo_o\,(1-e^{-t_3/R_sC_L})$

$.9 = 1 - e^{-t_3/R_sC_L}$, $.1 = e^{-t_3/R_sC_L}$

Taking the ln of both sides:

$\ln .1 = t_3/R_sC_L$

$$t_3 = R_sC_L \ln .1 = 2.3\, R_sC_L \qquad \text{Equation 9a}$$

since $.9\,E_o/1.0E_o = t_3/t_1$

$$t_3 = .9\, t_1 \qquad \text{Equation 10a}$$

Substitute Equation 10a in Equation 9a

$$.9\, t_1 = 2.3\, R_sC_L$$

or

$t_1 = 2.3/.9\ R_s C_L = 2.5\ R_s C_L$ Equation 11a

The above Equation holds true for wave front provided E_o is equal to the crest value reached. This means that C_L must be small compared to C_g and that R_s is held to as small a value as possible.

The above Equation also assumed that the inductance of the discharge circuit was very small which is usually true for impulse generators. The assumption of constant E_o and small inductance are compatible because the effect, if any, of the inductance in the circuit is to keep E_o constant.

Tail of wave (discharge time)

For this calculation the equivalent circuit of Figure I would be as Figure IV.

R = Effective Resistance to Ground

C = Effective Cap to Ground Includes C_L and C_g.

Inductance is again Neglected

Figure IV

Let E_o again equal the crest voltage reached.

Then at any time t_n, the voltage (Vc) across C equals the voltage drop across R.

$Vc = E_o = 1/c \int idt = V_R = iR$

$iR = E_o = 1/C \int idt$ 1b

The above Equation is similar to Equation 1a and the boundary conditions of $V_R = iR$ at $t = o$ is the same, therefore, the solution will be the same.

$$i = E/R\, e^{-t_n/RC} \qquad 2b$$

AIEE standards #4 define the limits in microseconds of the tail as the time t_1, plus the time from t_1 to t_2 as in Figure V.

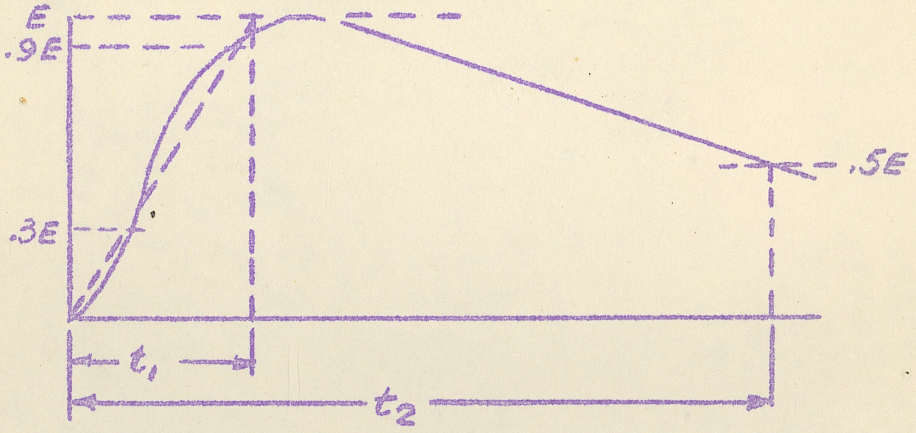


Figure V

Substituting in Equation 2b for the time when $V_R = .5E$

$$i = .5E/R = E/R\, e^{-t_4/RC} \qquad 3b$$

$$.5 = e^{-t_4/RC} \qquad 4b$$

$$\ln .5 = t_4/RC$$

$$t_4 = .6932\ RC \qquad 5b$$

Since $t_2 = t_1 + t_4$

$$t_2 = t_1 + .6932\ RC \qquad 6b$$

$$C = C_g + C_L + C_s \qquad 7b$$

$$R = R_g\,(R_s + R_g)/R_g + R_s + R_d \qquad 8b$$

then equation 6b becomes approximately:

$$t_2 = t_1 + \frac{.7\ R_g\,(R_s + R_d)\,(C_g + C_L + C_s)}{R_g + R_d + R_s} \qquad 9b$$

LOCKE Incorporated, Baltimore, Maryland
EUGENE DIETZGEN CO. NO. 346

ENGINEERING DEPARTMENT
PRINTED IN U.S.A.

CURVE 5LSV-1-A

CALIBRATION OF 5 UNIT GENERATOR WITH LOAD CAPACITOR AND 25 CM. SPHERES 1.5 X 40 μ. SEC. WAVE

KV CREST

500
400
300
200
100
0

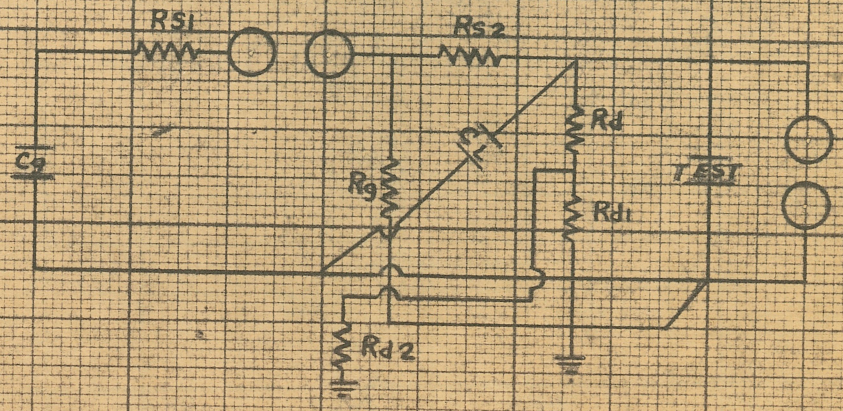
0 40 80 120 160 200 240 280 320

LOWER SIDE VOLTS (RMS)

+ POSITIVE
⊙ NEGATIVE

C_L = 1500 μμf
C_g = 0.33/10 μf
R_{s1} = 50 Ω
R_{s2} = 270 Ω
R_d = 4985 Ω
R_g = 3000 Ω
R_{d1} @ 0-100 KV = 125 Ω
@ 100-350 KV = 40 Ω
R_{d2} = 75 Ω
CHARGING TIME - 20 SECS.

RESISTORS
18 - 15's
20 - 250's
12 - 250's



4-8-52

S.E.A.

CURVE 10 LSV-1-A

CALIBRATION CURVE FOR 10 UNIT GENERATOR

1.5 X 40 μs. WAVE

KV CREST

1000
900
800
700
600
500
400
300
200
100
0

0 40 80 120 160 200 240 280

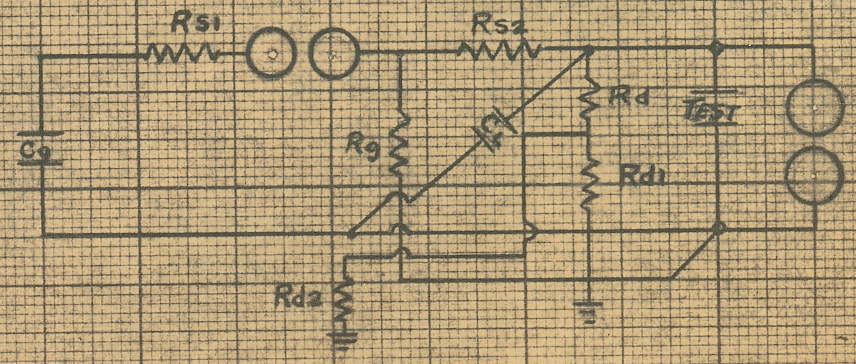
LOWER SIDE VOLTS (R.M.S.)

NEGATIVE
POSITIVE

+ POSITIVE
⊙ NEGATIVE

C_g = 0.33/2.0 μf
C_L = 600 μμf
R_{s1} = 100 Ω
R_{s2} = 530 Ω
R_d = 19,900 Ω
R_{d1} = 75 Ω
R_{d2} = 75 Ω
R_g = 4110 Ω
C_s = 480 μμf approx.
CHARGING TIME - 30 SECS.
USE 8 FT. OF BRAID FROM TOP OF R_g RACK TO PULLEY

RESISTORS
18 - 30's
40 - 500's
33 - 125's



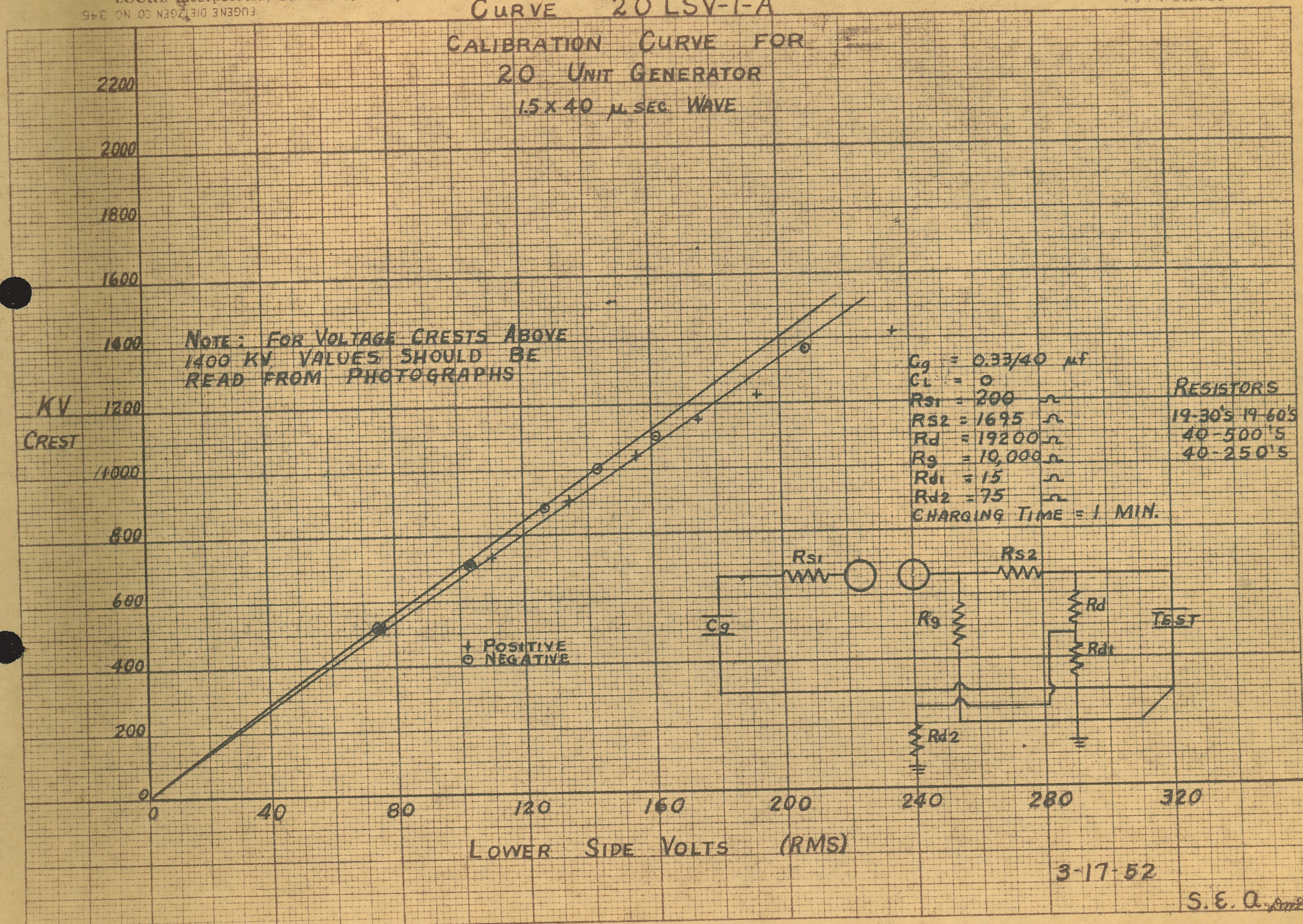
2-27-52

S.E.O.

CURVE 20 LSV-1-A

CALIBRATION CURVE FOR 20 UNIT GENERATOR

1.5 x 40 μ. SEC. WAVE



3-17-52

S.E.A.

EUGENE DIETZGEN CO. NO. 345

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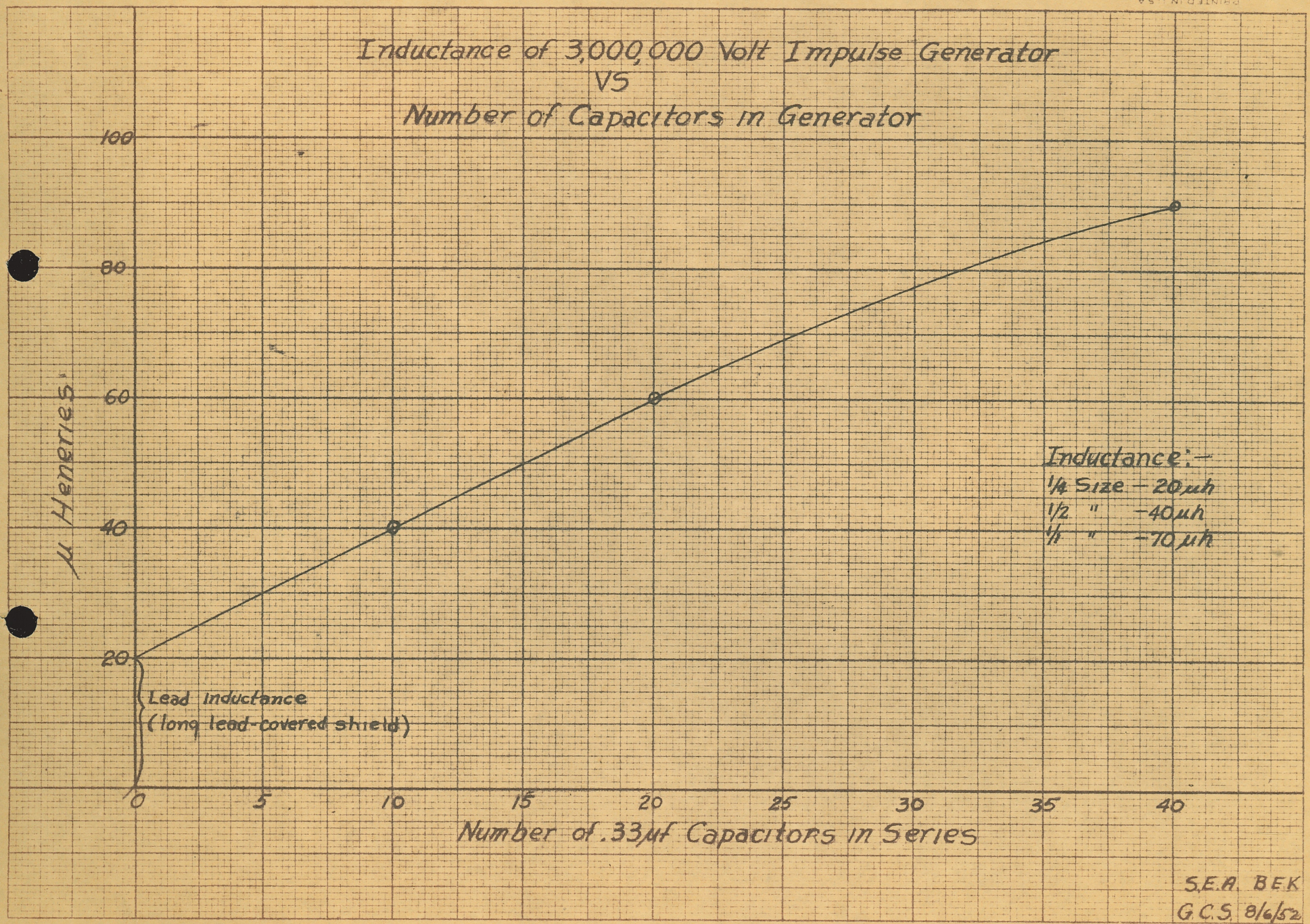
Inductance of 3,000,000 Volt Impulse Generator VS Number of Capacitors in Generator



S.E.A. BEK
G.C.S. 8/6/52

LARGE MOTOR GENERATOR SET (M.G. SET)
STARTING AND SHUT-DOWN PROCEDURE

Author:

E. E. Pfeiffer

Approved:

A. L. Libby

HIGH VOLTAGE AND MECHANICAL LABORATORY
INSULATOR PRODUCTS DEPARTMENT GENERAL ELECTRIC COMPANY BALTIMORE, MARYLAND
August 31, 1971

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III. STARTING AND RUNNING PROCEDURE

IV. SHUT-DOWN PROCEDURE

V. SAFETY

LARGE MOTOR GENERATOR SET (M.G. SET)
STARTING AND SHUT-DOWN PROCEDURE

I. INTRODUCTION

When starting the M.G. set, only half voltage (6 900 v) is used, and the motor starts as a three-phase, wound-rotor ~~introduction~~ Induction type.

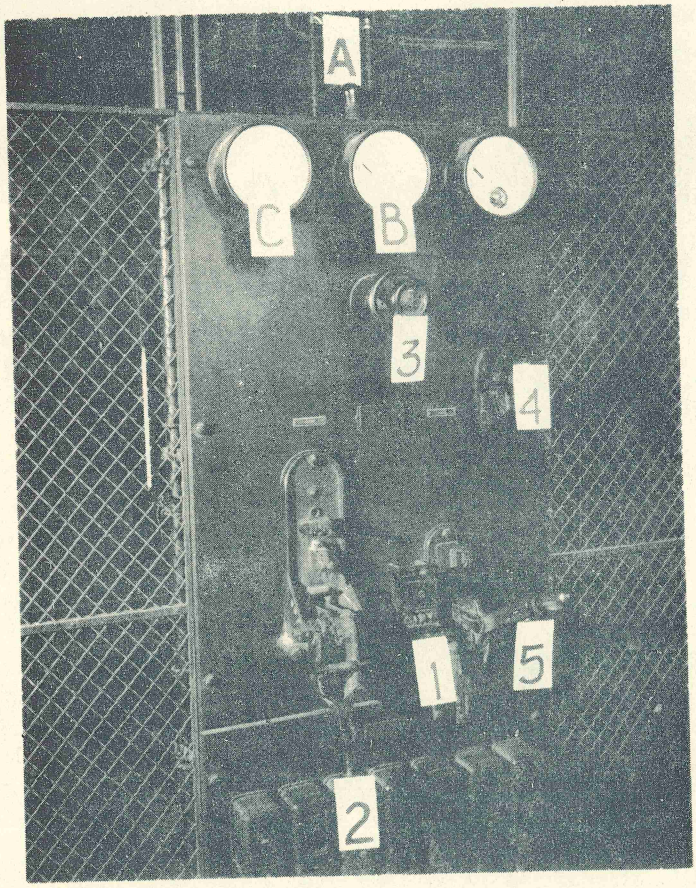
After the D.C. exciter is adjusted to 125 volts, it is fed into the motor's field making the motor a synchronous type.

When the field current has stabilized, the starting 6 900 volts are released and the full 13 800 running volts are quickly applied.

The motor is connected to a three-phase generator with a controlled variable field resistance, operating at 62.5 Hz.

Although provisions are made that each phase can be tied to a separate transformer, all testing is made using a single-phase tied to a single transformer, or three transformers in cascade.

II. STARTING AND RUNNING PANEL WITH LOCATED OPERATING POINTS.



A. Neon bulb.
B. D.C. Volt Meter
C. A.C. Ammeter

1. Under Voltage relay.
2. Starter lever.
3. Resistance control knob. Motor fld. Res.
4. Small D.C. lever Motor fld. Sw.
5. Running lever.

D.C. Ammeter (not marked) above #4, D.C. lever.

III. MOTOR-GENERATOR

Step-by-Step Starting and Running Procedure

1. Open generator room wooden doors to garage. Tie left door against stop and leave metal fence door open until M.G. (motor generator) set is running.

2. Open both front windows unless outside temperature is below 40°F, in which case only one window need be opened.

3. Note that neon bulb "A" (top of control panel) is lit. This indicates that the 13,000 volts needed to run the M.G. set are available.

4. Close under voltage relay #1.

5. Be sure that the small D.C. switch, #4, and large running lever, #5, are open with handles in "out" position.

6. Turn resistance control knob, #3, to maximum clockwise position (all resistance in).

7. Disengage catch and lower starting lever, #2, until roller pin is below hammer of the switch mechanism.

8. Close starting lever, #2. Motor will start revolving.

9. While M.G. set is gaining speed, check all six oil rings: rings must be turning on shaft and oil flowing with them. Check oil level in all three cups, at center, and end bearings. The M. G. system will pass through one resonant speed and vibration will be felt for a few seconds.

10. Adjust resistance knob, #3, to maintain 125 D.C. volts.

11. The A.C. Ammeter - "C" - will oscillate between six to fourteen amps as the M.G. set reaches full speed. When the A.C. ammeter "C" cycles to its lowest reading (six ±), close the small D.C. lever, #4. The A.C. ammeter "C" will cut out and the D.C. ammeter (above #4) will register between 25 and 26 D.C. amps.

12. At the completion of Step 11, it will be necessary to readjust the resistance knob, #3, resetting D.C. volts to 125.

13. Before changing from starting to running, be sure that the meters are relatively stable, with no oscillating of the D.C. volt- or ammeter, and only a very slow movement (about two amps) indicated on the A.C. ammeter.

A C ammeter does not cut out, it only stabilizes to a lower reading when motor Syncronizes

14. Final Step -- to change from starting to running. With the meters stable (as in Step 13) hold the handle of the starting lever, #2, with the left hand and release the catch which holds the lever in place with the right hand. When the catch is free, release the starting lever and allow it to fall open, then very quickly close the running lever, #5. This change from starting to running should be made in no more than two to three seconds.

15. Recheck the D.C. voltage, adjust if necessary with knob #3 to 125 volts. If the M.G. set is started at the beginning of the working hours, this step should be checked at intervals of every two or three hours because of the G.M. room rise in temperature. Because of this temperature rise, the resistance may have to be adjusted to maintain a 125 volt level.

16. Close and latch the south metal screen door, also the M.G. door when returning to the laboratory.

17. Should a problem develop at any time during starting, flip open the under voltage relay, #1; the starting lever, #2, should be open; proceed through the shut down steps.

Check problem, correct, repeat start-up procedure steps.

IV. M.G. SHUTDOWN PROCEDURE

1. Flip open the under voltage relay, #1. This releases the mechanical holding device and allows the running breakers to open. The running lever, #5, which is now disconnected can be moved to the open position.

2. Turn resistance knob, #3, to maximum clockwise position, thereby putting all resistance in the field circuit.

3. While the M.G. set is slowing down, close the outside M.G. room doors, the metal fence door, and lock them. Close the two windows.

4. The M.G. set should by now have slowed down enough to allow the D.C. ammeter to drop below three amps. When at three amps, or lower, open the small D.C. lever, #4.

5. All necessary disconnections have now been made, and the M.G. set will slowly come to a stop. The door to the laboratory should remain open at end of shut down.

SAFETY

1. Check to be sure the doors and windows are open, as described in Steps 1 and 2.

2. Prior to performing Step 9, remove all loose articles from shirt pockets as they could fall into M.G. set while in motion.

3. Always check the panel before starting M.G. set.
   Check: Mean bulb "A" -- if lit.
   Small D.C. lever #4 -- if open.
   Field switch -- horns and contacts.

10/3/80

Check out resonance of 3 trans. with a capacitive load of 2500 pf / 3000 pf.

3,166 pf.

$X_L = 2\pi f L =$

$L = \frac{8.38 \times 10^5}{6.28 \times 60} = .0222 \times 10^5 = 2.22 \times 10^3$

$= 2,220$ henries

3 transformers

(assuming $X_C = X_L$ Solve for L)

$X_C = \frac{1}{2\pi f C}$

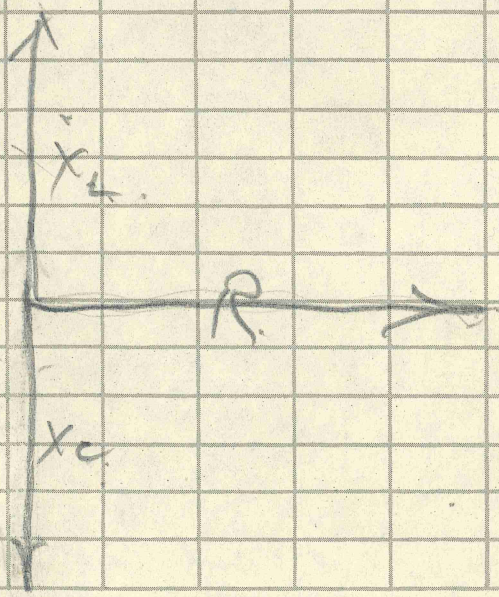
$\frac{10^{12}}{6.28 \times 60 \times 3,166 \text{ pf}} = .000838 \times 10^7$

$= 8.38 \times 10^5$

$\frac{1}{3.166 \times 10^3}$

838,000 Ω

X_C



2530 pf = 2,785 henries

3,000 pf = approx. 2300 h

3,166 pf = 2,220 henries

HIGH VOLTAGE AND MECHANICAL LABORATORY

PROCEDURE FOR HANDLING TEST REQUISITIONS

A. L. Libby

INSULATOR PRODUCTS DEPARTMENT GENERAL ELECTRIC COMPANY BALTIMORE, MARYLAND

June 29, 1971

HIGH VOLTAGE AND MECHANICAL LABORATORY

PROCEDURE FOR HANDLING TEST REQUISITIONS

I. INCOMING REQUISITIONS

Incoming test requisitions will be assigned a sequence number and entered into the "Record of Test Requistions" High Voltage Laboratory. Usually this will be done by the laboratory technician normally assigned to this task, but any High Voltage Laboratory technician may make this entry.

Carbon or duplicate copies of test requisitions will be numbered and returned to their originators by the person numbering and recording the requisition. Requisitions should be on Form BQC-800-2.

A separate tab folder will be numbered for each test requisition and the requisition put into it.

II. SCHEDULING

All requisitions will be entered into a Job Log. Requisition folders will then be put into the "Active Test Requisitions" file, except as needed for immediate test or as requested by the Laboratory Supervisor.

III. REPORTING AND DISTRIBUTION OF COMPLETED REQUISITION TEST REPORTS

A. Requisition Close-Out

When all work is completed on a test requisition, it is to be closed as follows, usually by the technician specifically assigned this responsibility:

1. Enter Date-Closed and the initials of the person handling the closing into the Record of Test Requisitions.

2. Number the report sheets in sequence starting from 1 on the requisition form, BQC-800-2.

3. Completed or cancelled tests covered in the requisition are to be checked off in the Job Log.

4. Folders continaing reports are to be used again. The test requisition number is to be erased and the folder put in the back of the file titled "Active Requisitions".

5. Reports, including data sheets and test requisition sheets are to be taken to the reproduction room.

B. Reproduction and Distribution

Reproduction will copy with blueprint or other machines, as required, the data and requisition sheets which together make up the Test Report. Test reports are to be copied in sufficient quantity to meet the distribution requirements. Copies are then marked for distribution and put in to the Department mail.

One copy of each test report is to be sent to the High Voltage and Mechanical Laboratory to be filed in the completed requisition file according to requisition number.

Original data sheets, with the requisition sheet/s/, are to be filed in the Product Engineering file by test report/requisition number.

IV. REPORTING AND DISTRIBUTION OF PARTIAL REPORTS

A. When to Distribute a Partial Report

Requisitions requiring aging, time load, or other tests that will require extended periods to complete should be distributed prior to completion. Partial distribution will normally be made when tests completed will not be followed by other tests for more than one month.

A partial report will be made also on an aging or time load test when more than one month remains before the requisition is completed.

B. What and How to Distribute

Normally the requisition sheet/s/ and all data sheets not previously distributed will make up a partial report. Data sheets are to be numbered in sequence, but the space for total number of pages is to be left blank.

The word "Partial" is to be written in pencil on the top of the test requisition. It is to be erased when the requisition is completed. The test requisition is to be at the first of the report, and assigned to page one.

When partial aging test results are reported, as a six-month result on a two-year test, the data sheets showing the test results are to be numbered with the proper report number and page numbers. The data sheets are to be distributed along with those pages of the requisition that (1) describe the insulators tested and (2) describe the aging test being run. Originals and a copy of the distribution are to be returned to the Laboratory file.

When requisitions, such as for Project Pearl, have supplements issued and tests run over a long period of time, only the latest data sheets and latest supplement will be distributed at a time. The data sheets should note the applicable supplement after the requisition number.

Reports, including data sheets and test requisition sheets, are to be taken to the reproduction room with a pink, "Partial Report" form attached.

C. Reproduction and Distribution

Reproduction will copy with blueprint or other machines, as required, the data and requisition sheets which together make up the test report. Enough reports are to be copied to meet the distribution requirements. Reproduction will mark copies for distribution and put them into the Department mail.

One copy of the partial test report is to be distributed to the High Voltage and Mechanical Laboratory as a record of the distribution. Original data sheets and test requisition sheets are to be returned to the laboratory also.

D. After Distribution of a Partial Report

Original data sheets that have been distributed are to be marked with a "D" and dated in the upper left corner when they are returned to their test requisition folder. When original data sheets have been checked against copies distributed and marked "D", the distribution copy may be destroyed.

Laboratory folders not in immediate use should be returned to the active requisition file.

APPENDIX

FORMS FOR HANDLING LABORATORY REQUISITIONS

TEST REQUISITION

HIGH VOLTAGE
AND
MECHANICAL LABORATORY

Engineering Index _____

Test Number _____

Page _____ of _____

Date Entered _____

Date Material Avail. _____

Date Closed _____

Closed By _____

Tests Requested By _____ Date _____

Who is to Witness Tests? _____

Report Copies To:

Lab File

CUSTOMER, PROJECT OR
OTHER REFERENCE _____

Assembly
Date

MATERIAL TO BE TESTED

TESTS REQUIRED
(Reference, ANS, or
Other Standards)

LABORATORY NOTES

TO: Blueprint and Reproduction Room

Please copy and distribute the attached partial lab report to:

_____

_____

_____

_____

_____

Please return original sheets and one copy to:

_____ (test req. _____)

High Voltage and Mechanical Laboratory.

GENERAL ELECTRIC

ELECTRIC UTILITY ENGINEERING
OPERATION

MAIL ADDRESS:
1 River Road
Schenectady, N.Y.
June 9, 1965

COPIES:

SUBJECT

ELECTRIFICACION DEL CARONI, C.A.
400-KV Tower Insulation Design
Study

Messrs. Kaminski
~~Kingsbury~~

Please return to M.A.S. for file.

~~Miss Mary Stack~~
2525 Insulator Drive
BALTIMORE

Dear Miss Stack:

A copy of this report has been mailed to R. E. Bauer in accordance with his request. This was a customer study and the results are proprietary to General Electric Company.

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RLT:pms
Encl.

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ELECTRIFICACION DEL CARONI, C.A.

400-KV TOWER INSULATION

DESIGN STUDY

May 4, 1965

L. O. Barthold
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General Electric Company
Schenectady, New York

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INTRODUCTION

The Tower Insulation Design Study developed recommendations of insulator string length and clearances to tower steel required to achieve satisfactory operating performance.

Lightning, switching-surge, and sixty-cycle conditions were considered independently, and the required number of insulators and air gap clearances were determined on the basis of the limiting (most severe) condition. Data from extensive flashover tests conducted both in the laboratory and with full-scale outdoor towers were used to determine the switching-surge strength of alternate designs. Tower insulation design conclusions are based in part on the results of the Lightning Outage and Switching-Surge Studies.

Mechanical design considerations are beyond the scope of this study, and recommendations are limited to electrical requirements which the mechanical design must meet.

I. LIGHTNING PERFORMANCE

Based on achieving a lightning trip-out rate below 5 per 100 miles per year, the Lightning Outage Study demonstrated that counterpoise will be required. With counterpoise, the lightning trip-out rate shows little variation with number of insulators for the insulator string lengths being considered. Therefore, the lightning trip-out rate will not be the limiting criterion for tower insulation design.

II. SWITCHING-SURGE PERFORMANCE

Switching-Surge Voltage : Resistor Preinsertion

The Switching Surge section of the report shows maximum switching-surge levels with resistor preinsertion of 2.2 per unit for three-pole energization and 2.4 per unit for three-pole reclosing.[1] These values are based on the ultimate system (as planned through 1986).

The ultimate system will have no shunt magnetic devices on certain line sections. Therefore, essentially full trapped charge may be present during high-speed reclosing. Also, with the initial system and reclosing times on the order of 25 cycles, a high percentage of the trapped energy will still be retained in the form of an oscillatory voltage. Thus, the design should be based on the reclosing surge to allow for the satisfactory application of high-speed reclosing.

Switching-Surge Voltage : Without Resistors

The TNA Study showed maximum switching-surge levels without resistor preinsertion of 3.0 per unit for three-pole energization and 4.5 per unit for three-pole reclosing. With single-pole reclosing, the maximum surge was limited to 2.2 per unit.

It is recommended that three-pole reclosing without resistors be avoided. A design based on the 4.5 surge level would be very costly and would require extremely

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1. 1.0 per unit $= \frac{400}{\sqrt{3}} \times \sqrt{2} = 326$ KV.

The maximum operating voltage is assumed to be 5% above nominal (400 KV).

large structures compared to those required with the alternatives of resistor preinsertion or single-pole reclosing. Also, three-pole reclosing without resistors would not be desirable with a tower design based on a lower surge level, since approximately 25% of the surges would exceed 3.0 per unit.

Switching-Surge Design : Resistor Preinsertion

To minimize switching-surge trip-outs, the wet switching-surge withstand level should be greater than the maximum surge level.[1] Since the bulk of test data available is on a critical flashover (CFO) basis, the design withstand level will be converted to an equivalent design CFO level.[2]

The design CFO level with resistor preinsertion would be 950 kv, wet, determined as follows:

$$\frac{400}{\sqrt{3}} \times \sqrt{2} \times 2.4 \times 1.10 \times 1.10 = 950 \text{ KV}$$

Line-to-ground factor = $\sqrt{3}$

Crest factor = $\sqrt{2}$

Maximum surge = 2.4 per unit (three-pole reclosing)

CFO : Withstand ratio = 1.10

Maximum atmospheric correction = 1.10 (including effect of altitude and daily variations)

Assumes reasonably clean insulators and a self-supporting tower of typical thickness (longitudinal).

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1. Withstand is defined as the voltage below which no flashovers will occur. The absolute withstand is very difficult to determine accurately. For purposes of this report, "withstand" will refer to a virtual withstand, where the probability of flashover is less than 1%.

2. Critical flashover is defined as the voltage at which the probability of flashover is 50%. Based on extensive test experience, the ratio of CFO to virtual withstand will be assumed to be 1.10.

The 950-kv wet CFO design criterion would be met by a design of 18 insulators with a minimum clearance to tower steel of 104 inches (2.65 meters) at a 15° swing angle.

The design clearance is based on maintaining a 15° clearance at least equal to the length of the insulator string (5.75 inches x number of units). Tests have shown this clearance relationship to result in an efficient design, balancing tower size with the effect of tower proximity on the flashover strength of insulators and air gaps. The selection of a 15° design angle is based on past METIFOR studies of a variety of weather patterns which showed that only about 15% of the time will the swing angle exceed 15° at any point on the line. These swing calculations include very conservative assumptions, and actual swings are expected to be much less than calculated. These studies used weather samples from a northern Minnesota location where the winds are reasonably severe and steady. A wind span to weight span ratio of 1.0 was assumed, but the swing angle frequency distribution does not vary significantly with moderate changes in this ratio. The hanger length is not critical except as it is required to achieve the proper clearances. The design is not based on the maximum swing angle, since the probability of a maximum surge occurring during maximum swing conditions is very small.

Switching-Surge Design : Without Resistors

The design CFO level without resistor preinsertion would be 1190 kv, wet. This level is based on a maximum surge of 3.0 per unit; it is assumed that three-pole reclosing without resistors will not be utilized.

The 1190-kv wet CFO design criterion would be met by a design of 26 insulators with a minimum clearance to tower steel of 150 inches (3.8 meters) at a 15° swing angle.

For comparative purposes, Table 1 shows the switching-surge strength of designs with from 17- to 30-unit insulator strings. In each case, the 15° clearance is assumed equal to the insulator string length. The per-unit surge corresponding to the withstand strength of each design is also shown. Table 1 emphasizes the problems that would be associated with attempting to design for a 4.5 surge, since a 30-unit design has a withstand strength corresponding to a per-unit surge of only 3.35. Table 1 shows that a 21-unit design would have a wet CFO of 1050 kv corresponding to a per-unit withstand of 2.65. With the 3.0 surge distribution, the 21-unit design would have a flashover probability of less than 0.5%, assuming that wet conditions prevail 6 hours a day for 8 months of the year. Based on the relative costs, it is recommended that if resistor preinsertion is not applied, this small flashover probability be accepted and the 21-unit design be adopted. This probability corresponds to one flashover for every 200 switching operations.

Phase-to-Phase

Insulation designed to meet phase-to-ground requirements will be adequate for phase-to-phase conditions. On their respective per-unit bases, phase-to-phase insulation levels will be greater than phase-to-ground, since the phase-to-phase insulation will be 2 x (phase-to-ground insulation) while the phase-to-phase voltage will be $\sqrt{3}$ x (phase-to-ground voltage). Phase-to-phase switching-surge voltages have been found to be lower than phase-to-ground surge voltages on their respective per-unit bases.

III. SIXTY-CYCLE PERFORMANCE

The two major considerations in evaluating 60-cycle performance are the strength of air gaps at extreme swing angles and the 60-cycle flashover strength under contaminated conditions. Contamination will be discussed in the following section; this section will consider the extreme swing criterion.

Extreme Swing

METIFOR calculations have shown that swing angles in excess of 50° are not unlikely. Therefore, it is recommended that the clearance to tower steel at a 60° swing angle be sufficient to withstand the crest 60-cycle voltage. Assuming a 10% air density correction, a CFO : Withstand ratio of 1.20, and a 10% safety factor, previous test results show that a 40-inch (1 meter) clearance would be required.[1]

An approximate hand calculation of these clearances indicates that the clearance at a 60° swing angle will be the limiting clearance for the outside phases of both the 18- and 21-unit designs.

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1. For conservatism, the CFO : Withstand ratio was increased to 1.20 to represent an "absolute" withstand rather than the "virtual" withstand used in switching-surge calculations.

IV. CONTAMINATION

In this section, a moderately severe degree of contamination for a non-industrial, nonagricultural area will be assumed and the probable influence of contamination on switching-surge and 60-cycle performance examined. The contaminated switching-surge strength of the insulators will be assumed to be 80% of the clean, wet switching-surge strength. Experience in testing contaminated insulators has shown that the corresponding contaminated 60-cycle strength would be 65% to 75% of the clean, wet 60-cycle strength. (The relative influence of contamination in reducing flashover strength is somewhat less for switching-surge waveshapes than for 60-cycle waves.)

Effect on Switching-Surge Performance

The probability of maximum switching-surges occurring during the relatively short time interval during which insulators reach their minimum contaminated strength (a fog or light rain following a prolonged dry spell) is very small. For this reason, the contaminated switching-surge analysis will be based on maximum surges of 2.2 per unit with resistor preinsertion and 2.5 per unit without resistor preinsertion.[1] In each case, less than 10% of the surges on the EDELCA system would exceed the level selected.

Tests at the High Voltage Laboratory in Pittsfield have shown that contaminated flashover strength is independent of the tower proximity effect. Therefore, the clean, wet strength used as a reference for determining the contaminated flashover

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1. 1.0 per-unit $= \frac{400}{\sqrt{3}} \times \sqrt{2} = 326$ KV.

strength did not include a correction for tower proximity.

Table 2 shows the contaminated switching-surge strength of 17- through 30-unit insulator strings. The contaminated withstands are expressed in terms of the corresponding per-unit surge. Based on Table 2, the 18-unit and 21-unit designs satisfy the contaminated switching-surge strength criterion.

Effect on Sixty-Cycle Performance

Table 3 shows the contaminated 60-cycle strength of 17- through 30-unit insulator strings, assuming the contaminated strength to be 65% of the clean, wet strength. The contaminated 60-cycle withstand strengths are shown in terms of per-unit of the maximum crest 60-cycle voltage, assuming a maximum operating voltage 5% above nominal (400 kv).[1] Based on this table, an 18-unit insulator string would have a 53% margin between its contaminated withstand and the crest 60-cycle voltage of 342 kv. Contaminated 60-cycle strength is a critical design criterion, since the 60-cycle strength receives a continuous test from the operating voltage. With the exception of unusually severe contamination conditions, the contaminated performance of the 18-unit design should be satisfactory.

Broken Insulators

No allowance has been included for broken or damaged insulators. This consideration should not be critical from the standpoint of switching-surge or lightning performance. A broken insulator at one structure would have only a very minor influence on the surge flashover probability for the entire line. A 17-unit insulator string would have a 45% margin between its contaminated withstand and the crest 60-cycle voltage; therefore, sufficient 60-cycle strength should be maintained with a broken insulator.

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1. 1.0 per-unit $= \frac{400}{\sqrt{3}} \times \sqrt{2} \times 1.05 = 342$ KV.

V. V-STRINGS

Tower testing experience has shown that V-string assemblies have lower switching-surge strength than single-strings with the same number of insulators. The number of V-string insulators required to achieve CFO's equal to the 18-, 21-, and 26-unit single-string designs would be 22, 25, and 30 (assuming a clearance to tower steel equal to the length of the insulator strings). Significant factors in a comparison between single-strings and V-strings are summarized below.

Single-String Advantages

1. The total cost for insulators, hardware, and fittings is less than with V-strings.
2. Single-strings are less restrictive to tower contour, since only one connection point (hanger) is required.
3. Single-strings are mechanically simpler, and should require less maintenance.
4. Single-strings do not have the potential problem of becoming unweighted during high winds (a possible source of television interference).

V-String Advantages

1. V-strings permit closer phase-to-phase spacing and reduce the cost of rights-of-way and perhaps the tower truss (depending on the design).
2. Insulators suspended at a 45° angle have some advantage in contaminated strength.

3. With V-strings, the flashover strength is independent of wind velocity, since swing angle is not a factor.

It is the judgment of the authors of this report that the single-string vs. V-string argument is primarily an economic one. Unless significant savings are demonstrated for V-strings, single-strings are considered preferable. For the EDELCA system, right-of-way cost is not an important factor; therefore, single-strings are recommended.

VI. EXAMPLE TOWER LAYOUTS

Figure 1 shows a schematic of the tower tops for the 18-unit and 21-unit single-string designs. One-half of the tower top is shown (from center-phase suspension point to outside-phase suspension point). For the 18-unit design, a phase spacing of approximately 27.8 feet (8.5 meters) is required. For the 21-unit design, the phase spacing is increased to 30.2 feet (9.25 meters).

Also shown in Figure 1 is a contour above which additional structural members may be installed without decreasing the flashover strength of the towers. Such modifications may be desirable from either a structural or an aesthetic standpoint.

Figure 2 shows a schematic of the center phase with a 22-unit V-string assembly. Here, the width of the tower window is determined by the clearance to tower steel at equilibrium position. This clearance should be at least equal to the insulator string length. The insulator string should be at an angle approximately 45° from the vertical. Note that the lower portion of the tower leg can be modified provided it remains within the contour body shown.

The 22-unit V-string corresponds to the flashover strength of an 18-unit single-string. Therefore, if outside-phase single-strings were used in conjunction with the 22-unit center-phase V-string, they should have 18-units. The center-phase V-string assembly, used with outside-phase single-strings, would permit a reduction in phase spacing from 8.5 meters to 8.2 meters (27 feet).

VII. CONDUCTOR GROUND CLEARANCE

Minimum ground clearance requirements are largely a matter of opinion and judgment. For a 400-kv line with 350 meter spans, the 6th Edition of the National Electric Safety Code in the United States would require a minimum clearance of 35 feet (10.7 meters) for areas accessible only to pedestrians and 40 feet (12.2 meters) for areas accessible to vehicles. Since portions of the EDELCA lines will traverse areas accessible to vehicles, particularly agricultural vehicles, it is recommended that 40 feet (12.2 meters) be adopted as the minimum ground clearance under maximum sag conditions (generally assumed in the United States to correspond to final sag at 120°F, no ice, no wind). This clearance is believed to be conservative and to be justified through its precedent in the U.S. National Electric Safety Code.

The appropriate initial stringing (installation) sag-tension characteristics must be determined on the basis of maintaining the 40-foot clearance under final, maximum sag conditions.

VIII. CONCLUSIONS

1. Surge suppressing resistor preinsertion on the 400-kv circuit breakers would be desirable, since this is a significant factor in the achievement of optimum switching-surge performance.

2. For the EDELCA lines, single insulator-string assemblies are recommended for all phases.

3. Lightning considerations are not limiting in selecting the number of insulators.

4. The recommended design with resistor preinsertion is 18-unit insulator strings for all phases, with a minimum clearance to tower steel of 40 inches (1 meter) at a 60° swing angle or 104 inches (2.65 meters) at a 15° swing angle, whichever is limiting.

5. Three-pole reclosing is not recommended without resistor preinsertion. It would not be economical to design for satisfactory performance levels under this condition.

6. The recommended design without resistor preinsertion (assuming reclosing would be single-pole only) is 21-unit insulator strings for all phases, with a minimum clearance to tower steel of 40 inches (1 meter) at a 60° swing angle or 121 inches (3.08 meters) at 15°, whichever is limiting. This design would have a flashover probability of less than 0.5%. It is recommended that if breaker resistors are not used, this probability be accepted--based on the additional cost of the 26-unit design required to protect against the maximum surge level.

7. The recommended designs should provide satisfactory performance under moderately severe contamination conditions. Heavy industrial or agricultural contamination might require special measures.

8. No additional margin should be required for broken or damaged insulators.

9. A minimum ground clearance of 40 feet (12.2 meters) under maximum sag conditions is recommended.

TABLE 1

Wet Switching-Surge Strength of Various Designs

Insulators	Clean, Wet CFO	Clean, Wet Withstand	Clean, Wet Withstand in Per-Unit Surge[1]
17	915 KV	830 KV	2.31
18	955	870	2.41
19	990	900	2.50
20	1015	930	2.58
21	1050	955	2.65
22	1080	980	2.72
23	1110	1010	2.81
24	1145	1040	2.89
25	1175	1070	2.97
26	1205	1095	3.04
27	1235	1120	3.11
28	1265	1150	3.19
29	1295	1180	3.28
30	1325	1205	3.35

1. 1.0 per-unit $= \frac{400}{\sqrt{3}} \times \sqrt{2} \times 1.10 = 360$ KV,

where 1.10 is a correction factor to account for atmospheric variations.

TABLE 2

Contaminated Switching-Surge Strength of Insulator Strings

Insulators	Clean, Wet CFO No Proximity Effect	Contaminated CFO	Contaminated Withstand	Contaminated Withstand in Per-Unit Surge[1]
17	1025 KV	820 KV	745 KV	2.28
18	1065	850	775	2.38
19	1110	885	805	2.47
20	1155	925	840	2.57
21	1200	960	870	2.67
22	1245	995	905	2.77
23	1290	1030	935	2.87
24	1330	1065	970	2.97
25	1375	1100	1000	3.06
26	1415	1135	1030	3.16
27	1460	1170	1060	3.26
28	1500	1200	1090	3.35
29	1540	1230	1120	3.44
30	1580	1260	1150	3.54

1. 1.0 per-unit $= \frac{400}{\sqrt{3}} \times \sqrt{2} = 326$ KV.

The 10% atmospheric correction is not included, and air gap flashovers are not considered.

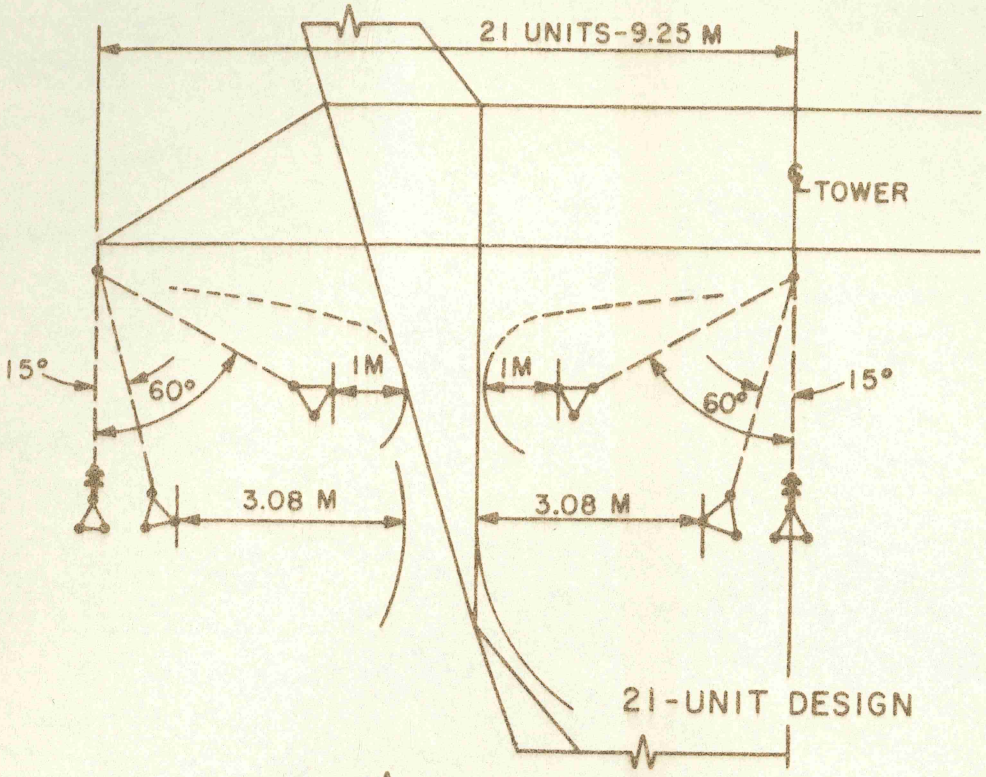
TABLE 3

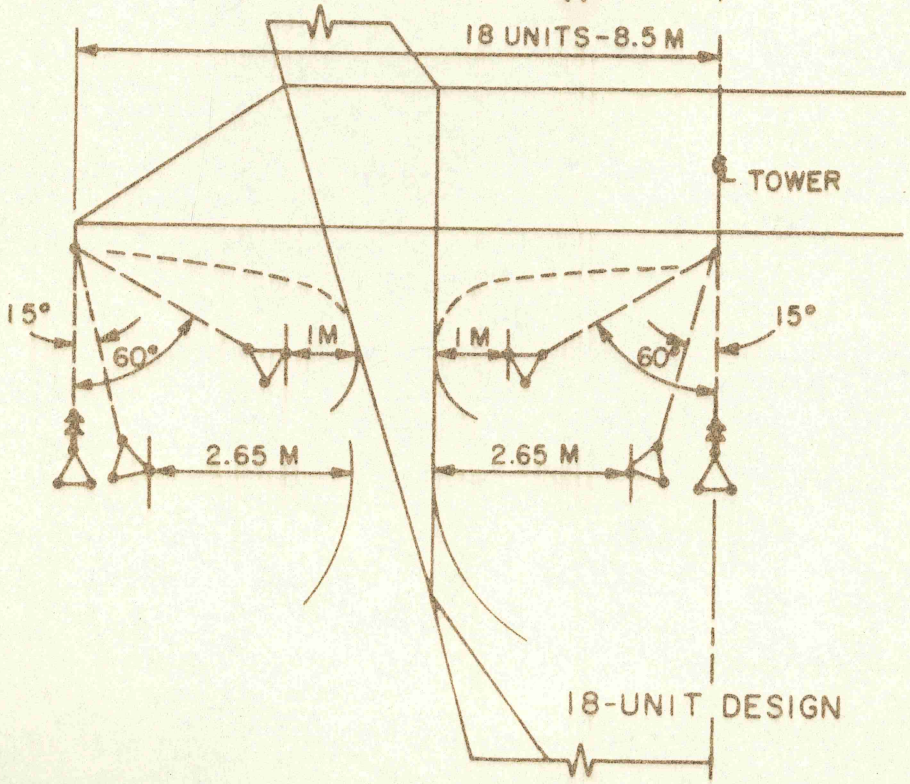
Contaminated Sixty-Cycle Strength of Insulator Strings

Insulators	Clean, Wet Crest CFO	Contaminated CFO	Contaminated Withatand[1]	Contaminated Withstand in Per-Unit of Max. Crest 60-Cycle[2]
17	920 KV	595 KV	495 KV	1.45
18	970	630	525	1.53
19	1020	660	550	1.61
20	1070	695	580	1.69
21	1115	725	605	1.77
22	1160	755	630	1.84
23	1205	785	655	1.92
24	1250	815	680	1.99
25	1290	840	700	2.05
26	1330	865	720	2.11
27	1370	890	740	2.16
28	1410	915	760	2.22

1. CFO : Withstand ratio of 1.20 assumed.

2. Maximum crest 60-cycle = $\frac{400}{\sqrt{3}} \times \sqrt{2} \times 1.05 = 342$ KV.



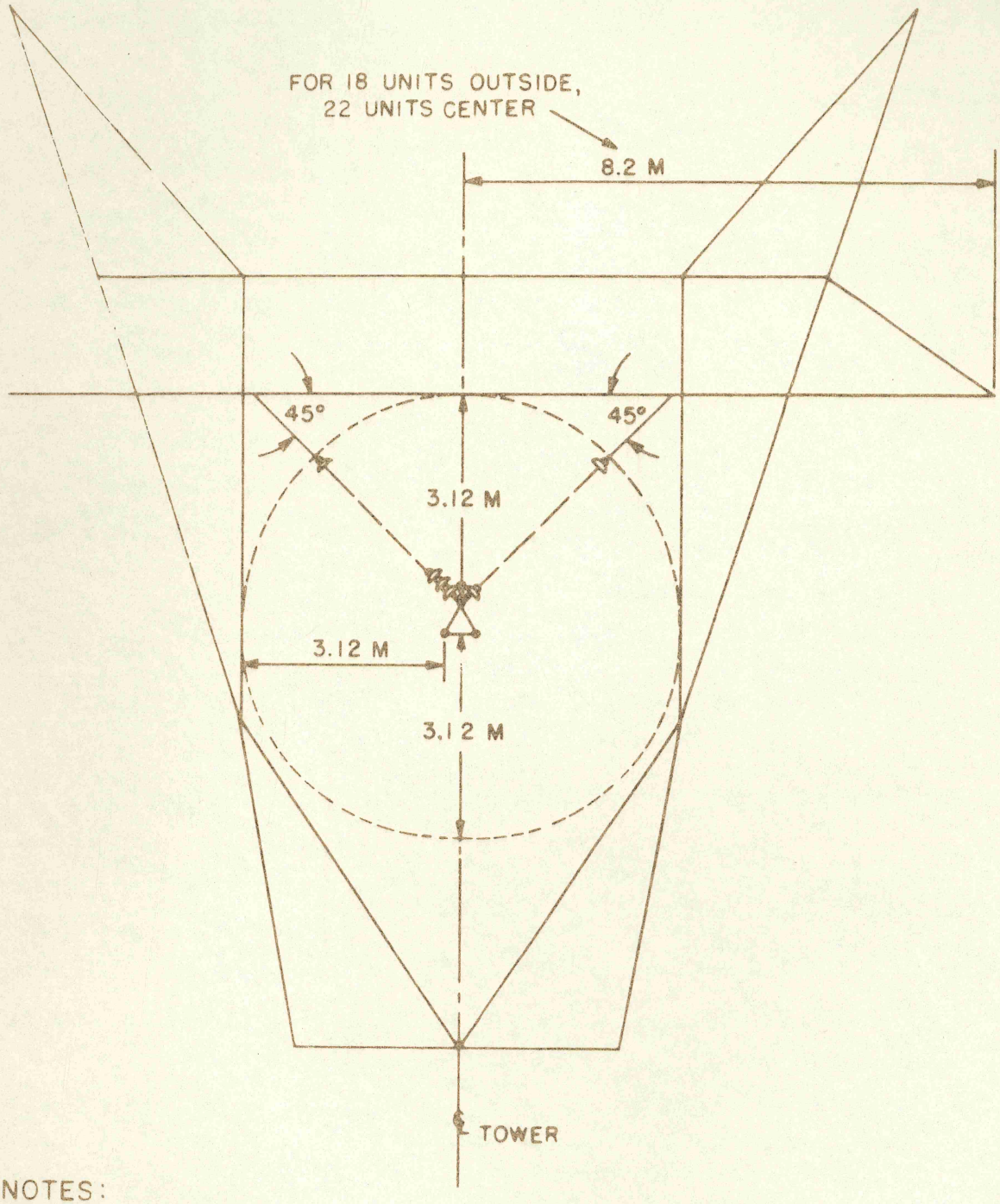


NOTES:

ALL DIMENSIONS APPROXIMATE
---BOUNDARY FOR OPTIONAL BRACING OR CONTOURING WITHOUT REDUCING FLASHOVER STRENGTH

EXAMPLE TOWER CONFIGURATION

FIG. 1



NOTES:

ALL DIMENSIONS APPROXIMATE

--- BOUNDARY FOR OPTIONAL BRACING OR CONTOURING WITHOUT REDUCING FLASHOVER STRENGTH

EXAMPLE TOWER CONFIGURATION
22-UNIT V-STRING: CENTER PHASE

FIG. 2

ANATOMY OF INSULATED TOOL WORK

by

Joe.

J. M. Van Name, Superintendent
Overhead Transmission Section
Philadelphia Electric Company

Presented to

Pennsylvania Electric Association
Transmission and Distribution Committee Meeting

Skytop Lodge, Skytop, Pennsylvania
May 18 and 19, 1967

ANATOMY OF INSULATED TOOL WORK

by

J. M. Van Name, Superintendent
Overhead Transmission Section
Philadelphia Electric Company

SUMMARY

The training of personnel in the Overhead Transmission Section in the practices to be followed during energized line work followed the prior training presented, and also, depended on the practices followed in maintenance and operation of the facilities of the Company. Through the use of demonstrations and the explanation of the why of each practice, confidence was obtained in the new concepts, and the employment of insulated tools is now standard practice in the accomplishment of line work.

Training emphasized the unit work or building block concept, and was divided into Phases covering the essentials related to each technique. De-energized techniques had been the standard practice. The new techniques of hot stick and bare hand were taught in a classroom-fashion, with a specific instructor. Upon completion of all Phases of the training, personnel became fully qualified in the new work concepts and have performed many diversified jobs with equipment still in service.

Prior and complete study of the entire concepts involved, the procurement of necessary tools and equipment, investigation of secondary effects, such as static charge, and demonstrations to familiarize all personnel with the normal and adverse events that may happen developed confidence, and inspired acceptance of the concepts.

Many seemingly small points were combined into an entire program that permitted the conversion to the new concepts at one time, and with the enthusiastic support of the Section's forces.

CHAPTER A

INTRODUCTION

The title of this presentation, "Anatomy of Insulated Tool Work Training", when analyzed, really involves the analysis of the training presented to the personnel working on a transmission line while it is energized from the first time he is placed on a structure through his advancement to a 1st class lineman. Each step in the individual's training is really related to insulated tool work by any method. Rigging principles are involved in each method, as an example, and proper initial training will permit the progression of the individual to insulated tool work methods with a minimum of re- or additional training.

Training requirements are also related to the design of a transmission system, methods of operation, construction practices, operational practices, and geographic considerations. The division of work among personnel influences the adoption of the concepts involved.

Only by considering the full extent and implications of the adoption of these new techniques, which permit the maintenance and construction of transmission lines operating at voltages from 69 KV to 500 KV, can supervision evaluate the subject that should be included in the training. Each company and system will have its specialized requirement.

The Philadelphia Electric Company will have over ninety miles of 500 KV line in service this year. These lines are part of the Keystone Project. The Company is an active participant in the Task Force concerned with the live line maintenance practices to be followed on these lines. Although specific mention is not made of the activities of this Task Force or the application of insulated tool work methods to EHV 500 KV line work, it is definitely applicable, and really provides the base of similar work at lower voltages.

The bare hand concept, wherein the workman is placed at line potential and at the work location, is really only applicable in conjunction with other methods, such as hot sticks. Strains must be supported by a structure through the employment of insulated tools; then the lineman using the bare hand concept may disconnect the part, as an example. He alone cannot support these strains.

A complete manual of Insulated Tool Work Practices is in preparation. Instructions have been issued, but many are being revised to reflect new developments, particularly with reference to their application to the Keystone Lines as they are presently designed. The basic training concepts and practices followed by the P. E. Co. are outlined herein for the consideration of other companies. Suggestions, comments and criticisms are welcomed.

The system concept adopted by the Philadelphia Electric Company considered the following in relation to the state of training of the personnel assigned to the Overhead Transmission Section:

a. Objective: To fully qualify all personnel in insulated tool work methods, which would permit the maintenance and operation of the aerial transmission system with the lines in service and carrying load without any increase in hazard to personnel.

b. Policies:

1. Provide adequate and complete training and training facilities.

2. Equip personnel with the required tools and equipment, and also the necessary static reduction equipment.

3. Explain the new concepts involved and prove their adequacy through demonstrations, tests, and explanations related to known facts.

4. Maintain an uncompromising attitude toward safety.

c. Programs:

1. Plan well in advance and publish the training programs to be followed. Orient personnel in the concepts early.

2. Qualify Company personnel in the concepts so that they may train other Company personnel.

3. Have available answers to all known questions, but do not attempt to "fool" the personnel.

d. Procedures:

1. Continue the same basic training philosophy during the integration of the new concepts into the work routines of the personnel.

2. Seek advice of all who may provide essential data. Have the Safety, and Methods and Training Departments take part in the development and training.

3. Use the "unit work procedure" or building block technique in the conduct of training.

4. Explain the "WHY" of all practices in each case.

5. Orient personnel early, brief them before the start of training, take notes during training, and critique each training procedure in detail.

Highlights of some aspects that are related to the training are included in this Paper. A Paper concerning the entire training program is in preparation, and should be available about July 1, 1967. Persons desiring a copy should forward their name, title, company, address and the number of copies desired to the author, c/o Plymouth Service Building, Ridge Pike and Chemical Road, Plymouth Meeting, Pennsylvania 19462.

The relationship of the existing and future components on the Philadelphia Electric Transmission System to the need for insulated tool work is included in brief form in this Paper. Work techniques are applicable to every transmission voltage and, with the proper training, personnel can make an intelligent selection of the practice or practices to be followed in accomplishing any specific job or task.

CHAPTER B

THE PHILADELPHIA ELECTRIC COMPANY TRANSMISSION SYSTEM

A. SCOPE

The overhead transmission system of the Philadelphia Electric Company System extends throughout the southeastern portion of Pennsylvania and the northern part of the State of Maryland. (Figure IV-1) (Note: All Figures will be found in Appendix IV). The area served is approximately 2300 square miles and has a maximum north-south extent of approximately 97 miles and a maximum east-west dimension of about 88 miles.

At present, the aerial line mileage is: (Figure IV-2)

VOLTAGE	CIRCUIT MILES (Aerial Lines)
220 KV	220
132 KV	155
69 KV	200

During the month of May, 1967, it is expected that approximately 90 miles of 500 KV line and approximately 30 miles of 220 KV double circuit line will be placed in service.

Not included in the above totals are the miles of line that are built for a higher transmission voltage, but presently in operation at a lower 33 KV voltage. These lines, when insulated for 69 KV or higher voltage are operated and maintained by the Overhead Transmission Section. There are approximately 100 circuit miles of line in this classification.

B. STRUCTURE TYPES AND CONSTRUCTIONS ARE VARIED:

They include lattice steel and aluminum towers, steel wide flange columns, round and Poly-12 steel poles, wood single poles and wood H-frame structures, and combinations thereof. (See Figures IV-3, 4, 5, & 6). Pole height average is 70-feet, with a maximum of 100 feet. The average height of steel towers is 100 feet, with a maximum height on the system of 345 feet; these towers are part of the crossing of the Delaware River near Chester, Pennsylvania, and are located on man-made islands in the river.

Structure weight average is 10,000 pounds for the steel towers, and the maximum weight of a tower, not including the special river crossing structures, is 153 tons.

C. CONDUCTOR SIZES:

There are 42 sizes of wire or conductor installed on the transmission system, ranging in size from 2/0 copper to 2,505 mcm AACSR wire, with a diameter of 1.904 inches and a weight of 2.925 pounds per foot.

The most common sizes are 795 mcm ACSR, both 26/7 and 30/19 stranding and 1,590 mcm ACSR, 54/19 stranding. The 500 KV Keystone lines employ a bundle of two conductors with a diameter of 1.821 inches. Each conductor weighs 2.341 pounds per foot.

The usual ruling span for lines on private Rights-of-Way is 1,200 feet. Along railroads, and in some congested areas, the average span is approximately 400 feet.

D. ELECTRICAL LOADS:

Transmission lines built since World War II were, in general, designed with 795 mcm ACSR as the phase conductor. These lines have a current rating of 1,200 amperes, and the wire size is employed on lines in all voltage classifications. Starting in 1966, standard construction used 1,590 mcm ACSR as the conductor and double circuit 220 KV aluminum towers as the supporting structure. Lines now being built on railroad Rights-of-Way also employ 1,590 MCM ACSR as the conductor.

Current ratings of the lines, when limited by the conductor, are approximately 1,200 amperes for 795 mcm ACSR and 500 MCM copper, 1,900 amperes for lines employing 1,590 MCM ACSR and 1,500 amperes-plus for each sub-conductor of the bundle used on the 500 KV Keystone transmission lines.

E. MECHANICAL LOADS:

The initial lines built for operation at 69 KV in the period 1915-1918 employed towers that supported 2/0 copper conductor with a maximum tension of about 3,000 pounds. The Conowingo Project (220 KV lines) used 795 mcm 30/19 ACSR strung at approximately 7,000 pounds; the maximum tension is 18,000 pounds.

In 1959, the crossing of the Delaware River south of Chester was installed. The conductor is strung at approximately 21,000 pounds. The new 220 KV lines employing 1,590 MCM ACSR are strung at about 10,000 pounds. The Keystone line employs a stringing tension of about 12,000 pounds per sub-conductor, making a total of 24,000 pounds per bundle or phase.

The special river crossing on the Keystone line located up-stream from the Conowingo Dam on the Susquehanna River has a conductor size of 1.904 inches; this conductor has an ultimate strength of 126,000 pounds and is strung at 24,000 pounds per sub-conductor of the bundle. Hence the 0-degree F., horizontal tension, unloaded, is 48,000 pounds.

Thus, the tensions encountered by line crews on the transmission system have increased from 7,000 pounds in 1928, to 21,000 pounds in 1959, to 48,000 pounds in 1967.

F. LOCATION OF LINES:

The area served by the Company includes the City of Philadelphia, and several other small cities. It also includes many square miles of rural area and farming country. The terrain is considered rolling, but there are several "hills" on which the Company has erected transmission structures (Figure IV-3). Thus, there is a wide diversity of terrain, and access to structures is diversified.

In addition, approximately 200 miles of the aerial transmission system are located on railroad rights-of-way, both electrified and non-electrified. This adds greatly to the access problem, and calls for ingenuity in working methods (Figures IV-7, 8 and 9).

Lines along railroad R/W mean also that the Company personnel must be familiar with, and work around, the railroad's transmission, signal, and catenary systems, and also maintain clearances, as required, to tracks.

CHAPTER C

SYSTEM ORGANIZATION

A. GENERAL:

Two major Departments are concerned with the design, construction, maintenance and operation of the aerial transmission system. The Engineering and Research Department is responsible for engineering and major line construction. Electric Operations includes the System Operation Division who is responsible for load dispatching, switching, and related functions and includes the Transmission and Distribution Department. The T. & D. Department maintains and operates the aerial transmission system.

B. ENGINEERING:

Within the Engineering and Research Department, a central group known as the Transmission Projects Branch handles major line design. Information required by this Branch is obtained from many sources, including a Material Group.

C. CONSTRUCTION:

Construction of major new lines is usually performed by contractors hired and supervised by the Construction Division of the Engineering and Research Department. Upon completion of the line, the plant is inspected by the Overhead Transmission Section (O.H.T.), and then placed in service, in conjunction with the System Operation Division. Upon placement in service, the line is the sole responsibility of the O. H. T. Section.

D. OPERATION:

Operation is directed by the System Operation Division (Load Dispatcher). This Division has a major office in the City of Philadelphia, and two smaller offices located at Plymouth Meeting and Morton, Pennsylvania. The offices operate the system through a Release, Permit and Restriction Procedure. Responsibility for lines is divided geographically, but only one office has the operating responsibility for the individual circuit or line.

E. THE OVERHEAD TRANSMISSION SECTION (O. H. T.):

This Section, directed by a Superintendent, is responsible for the entire aerial transmission system throughout the P. E. Co. System. Included are the lines in Maryland. In addition, through agreement with the Atlantic City Electric Company, the Section maintains and operates the Delaware River Crossing, south of Chester within the State of New Jersey.

The Section is headquartered at Plymouth Meeting, Pennsylvania, as this location provides good highway travel, and is roughly in the center of the aerial transmission system. All personnel of the Section work from this location.

The responsibilities of the Section include patrolling, maintenance, construction involving operating lines, R/W care and maintenance, painting, etc. Also, certain maintenance work for other departments, such as insulator testing, and river survey work are performed upon request.

Personnel include engineers, linemen, chauffeur-groundmen and a varying number of contractor personnel. The average work force is approximately 100 men.

CHAPTER D

BASIC EMPLOYMENT AND TRAINING

A. GENERAL:

To understand the reasons for the organization and training of the O. H. T. Section's personnel, and how energized line work techniques fit into the picture, it is necessary to provide a brief outline of the progression of a lineman from the date he is hired by the Company. This influences the final part of his training, wherein he is qualified in insulated tool work.

B. EMPLOYMENT:

All individuals employed for training as linemen are required to pass a qualifying aptitude test and a stringent medical examination, which includes a thorough back examination and X-ray. These tests have proven their value in detecting whether an individual will be able to qualify as a lineman, and advance through the progression periods to Lineman, First Class.

C. LINE SCHOOL:

Upon passing the initial tests and examinations, the individual is sent to a line school for a period of 6 weeks, during which time he is taught the fundamentals of climbing a pole, working on a pole, handling basic pole construction equipment, etc. Upon completion he is assigned to a distribution division or to the Overhead Transmission Section. Individuals may or may not have been earmarked for the O. H. T. Section at the time of employment.

D. BASIC O. H. T. SECTION TRAINING:

The line school only provided training in wood pole distribution construction and climbing methods. After this school, further training is conducted by the O. H. T. Section on steel towers, steel column structures, round steel poles, and the other varied structures on the transmission system. Occasionally one or two men from a line school class will not be adapted to climbing or working on these structures, or they cannot stand the heights involved. Quite often difficulty is experienced by linemen in climbing steel column structures where "skates" are used to support the man. (See Figure IV-10.) When this happens, the individual is transferred to a distribution division.

Individuals who still cannot "make the grade" in linework are released prior to the completion of the 6-month probationary employment period.

E. PROGRESSION TRAINING:

After learning the fundamentals of climbing on transmission structures, and becoming adapted to the heights involved, the new lineman is trained in many other phases of the work. These include the making of joints or splices on transmission-size conductors, use of hook ladders, operation of small boats, helicopter and other types of line patrolling, R/W maintenance, painting structures, railroad rules and regulations, etc. During the 52-months that pass between the time he is employed and the achievement of a classification as Lineman, First Class, Overhead Transmission, the individual must pass examinations in fundamental line work methods, rules, safety, etc. The three steps in the progression include certain courses, such as fundamentals of electricity, rigging methods, etc. For consideration for advancement, the individual must pass a trade qualifying examination consisting of a written examination and a performance examination in actual field work procedures and methods. Ratings by superiors are also considered in the final rating of the individual for advancement.

Chauffeur-groundmen are also given examinations, and advance through progressive rates of pay based on their ability to show adequate knowledge and good work performance.

Foremen are selected from linemen, and they also must pass a qualifying examination for advancement.

F. OTHER TRAINING:

Each employee of the Section must become qualified in other areas of work. These fields include passing of a heavy truck drivers examination, qualification in operation of winches and tension pulling equipment, operation of small boats, etc. Included for most personnel is a school in burning of steel. A welding school and qualification in Boiler Code welding are considered part of this specialized training.

Certain areas that required periodic inspection work by qualified lineman, such as paint inspection, R/W mowing and maintenance inspection, pole treating inspection, etc., are also considered areas of specialized training. The lineman is required to perform the actual work, and is taught the details of the trade job so that he may be qualified as an inspector on a contract job. Thus he is more capable to judge the quality of work performed by contractor personnel, and determine that it is accomplished according to the Company's standards and specifications.

CHAPTER E

CONDITIONS DICTATING CHANGE IN WORK METHODS

Several factors combine to make it desirable and necessary to convert the basic work methods of the O. H. T. Section from non-energized work to live line or insulated tool work methods. The transmission system was designed so that a line could be removed from service for maintenance during the '40s and '50s. However, increased loads, additional dual service customers, expansion of the system, and the great increase of work that must be accomplished in existing lines, all combine to make it virtually impossible to maintain the system without using some form of energized line maintenance.

Many miles of lines are now 30 years old, and require major maintenance work in the form of insulator and hardware replacement. Some lines were scheduled for re-conductoring in the '50s, but it became almost impossible to accomplish this work due to the limited time periods the lines could be removed from service.

As mentioned, the transmission system is composed of a large number of relatively short lines - approximately 10 miles in length. But the electrical loads are large, and substation and generation capacity connected to them involves a large block of power. Most lines have a current rating of approximatly 1,000 amperes at all transmission voltages. Hence, their removal from service involves a sizeable block of power.

The P. E. Co. system sits within the PJM Interconnection, and hence is called upon to transport large blocks of interchanged power between utilities of the interconnection. This also complicates the line outage problem.

Line electrical loads, increased tensions, physical location of lines, adjoining facilities, and other factors all pointed to the fact that maintenance work would have to be accomplished with the lines energized. This was realized in the '50s, and became a reality in the '60s.

However, it might be said that the Keystone 500 KV transmission system was the straw that broke the camel's back. These lines will form part of the backbone of the transmission system within the P. E. Co., in addition to carrying a sizeable generation into the System.

The physical size of the transmission line components, their weights, and the tensions employed dictate the use of light weight tools to accomplish much of the maintenance. Insulated tools provide this capability.

CHAPTER F

ENERGIZED LINE MAINTENANCE TECHNIQUES

Line work performed on electrical facilities generally falls within the two categories of work methods known as "insulation" and "isolation." The "insulation" concept means that the workman is insulated from the higher potential through the employment of rubber gloves, insulated sticks, etc. "Isolation" methods mean that the line or equipment is de-energized, and suitable protective devices are employed to prevent the establishment of a dangerous potential across or through the workman. De-energize the line and then "ground" it is the common practice for this method.

The practice followed until 1966 on the transmission system of the P. E. CO. was to perform work involving the normally energized parts of a line with the line out of service and grounds installed. Thus the equipment could not be employed to carry load. The factors outlined in Chapter E dictate that a change in this method would be required.

A. WORK TECHNIQUES AVAILABLE:

The Section had studied the work techniques available to accomplish maintenance on transmission lines for a long period of time. In general, they fall into three classifications:

1. De-energize the line. Here the line is taken out of service and blocked at the station ends. After a test for potential, grounds are installed by the workman to provide positive protection.

2. Employ Insulated Stick. An insulated stick, in combination with other devices, may be employed to manipulate the tools and components to permit the accomplishment of the maintenance work. This practice means that the man is at "earth" potential, and insulation is provided by the insulated stick, or "hot stick." At lower voltages, employed in distribution, this same protection is achieved by using rubber gloves.

3. Live Line techniques. Here the individual is brought to the line potential via a suitable insulating device. The device supports the man, as he is raised to the work location using an appropriate insulated device. The bare hand technique means that the man is at the line potential.

   He may be supported by the line itself, an insulated platform, aerial insulated bucket truck, etc. He is thus positioned at the work location, and can manipulate the tools and parts without the need of a long hot stick.

B. ACCOMPLISHMENT OF THE WORK TECHNIQUE:

As mentioned, there are two ways that the man can accomplish the work, and, at the same time, maintain the equipment in service. With these ways, however, there must be additional insulation or protection provided to maintain safety and prevent injury to the workman. The structure itself can be employed as the supporting item for the insulation and the workman; an insulated platform, or aerial bucket truck that is insulated, may be used to support the man; finally the energized equipment itself may be the supporting device.

When the energized part is used as the supporting device for the workman, we have the basic live line technique or bare hand method. This is the extension of the "bird-on-the-wire" concept. Birds sit on low voltage energized wires and are not injured, as they do not complete the electrical circuit. There is no difference of potential across or between any part of their bodies. Bare hand work employs this same basic concept.

Birds do not sit on the higher voltage lines due to the magnitude of the field around the wire, which prevents their approaching the energized equipment. This higher strength field also induces more current in the workman, and thus there is the requirement that he be shielded while in the field. The Faraday cage, or metallic shield, prevents the field from inducing the current in the man, and hence is employed at the higher voltages to the extent necessary.

Shielding may be achieved by using a metal cage, conducting suit, or other device. The metallic shield is bonded to the energized part, and thus there is no difference of potential across the workman, nor is there a field of sufficient strength around the man to induce a body current that is injurious.

C. SAFETY:

Safety is not compromised in any work operation when insulated tool work concepts are employed. Actually, there may be less hazard when the bare hand technique is employed.

In the case of work using rubber gloves or hot sticks, any leakage current passes through the lineman on its way to ground or earth. With a metallic shield around the man, or when the man is supported on an insulated platform and bonded to the energized part, any leakage current will pass from the part through the bond, and thence via the insulation to earth. It does not pass through the lineman.

During the demonstrations conducted in the training, the bare hand technique was illustrated. To prove the point concerning the leakage current passing around the man, and to show the results of a failure of the insulation under the man, the voltage on the conductor, to which the platform is bonded, is increased until flashover of the insulation occurs. This is approximately 126 KV in the laboratory.

There is no sensation to the man, nor does he feel any of the leakage current. This is also applicable to the power follow-up current. The insulator system should be designed so that any arc produced will not cause burning or other injury to the lineman, should a failure happen in the field.

Leakage current monitoring systems are employed in aerial lift devices to indicate the condition of the insulation. When placed directly on the energized part, like the bird, this additional device is not necessary, as the man is bonded to the part, and not supported by some other insulation that is in contact with earth.

Included as Appendix III is an outline of the considerations evaluated in the development of the bare hand technique in particular.

D. CLEARANCES:

Clearances, specified for de-energized work, are also followed in insulated tool work by the P. E. Co. Bonds (the new term for grounds) are applied with a stick of specified length after a test ("buzz" test) for the presence of potential is made.

The first bond is installed using a specified stick length and clearance. This is done so that, should the part be at a different potential, or the insulation system fail, the resulting power arc will not cause eye injury, burns, etc., to the man.

All bonds are of a design that provide sufficient capacity so that the voltage drop across one bond will be approximately 50 volts. Thus, with a 500 ohm man, there will be less than 1 milliampere of current through his body since he is in parallel with the bonds. Fault current capacity of the all-angle clamp and 2/0 bonding cable is 30,000 amperes.

CHAPTER G

INSULATED TOOL WORK TRAINING:
(See Appendix I for Course Content and Hours)

A. DEVELOPMENT:

As mentioned above in Chapter F, the development of insulated tool work by the P. E. Co. has proceeded over a long period of time. Actually hot sticks were used in line maintenance in the '20s. Hot stick work has been performed on high voltage lines since the '30s by many utility companies. During the period to the present, limited use was made of insulated tools and devices in conjunction with maintenance work on the system. The uses included clearance measurements using sticks and special string lines, installation of measuring devices for recording vibration on energized lines, removal of kites, strings, and wires from energized lines, and the determination of the condition of insulators using the live line insulator tester manufactured by the I. T. E. Company.

For the past fifteen years, all new tools and equipment were purchased and tested with an eye toward energized line maintenance. Thus, the Epoxiglas ladder, although initially used because of its superior strength characteristics, was also developed for the potential use as an insulated support platform for bare hand work. The All-angle ground clamp manufactured by the A. B. Chance Company was also designed to incorporate the features of a high-capacity jumper clamp, a bonding clamp, and a wire holding clamp. Polypropylene ropes have always been tested both mechanically and electrically to strict specifications so that it too could be used around energized equipment with safety.

B. ACTIVE INVESTIGATION:

Active investigation of the entire insulated tool work concept commenced in 1960. Other utility practices were studied, all possible methods investigated, and thought given to all phases of the work procedures. These studies again indicated the advisability of waiting until the conversion could be made at one time. This would preclude the re-training of personnel a second time when the bare hand concept was introduced after teaching hot stick methods.

Planning was commenced in earnest, and a complete review made of all present and proposed work practices. Included as specific points were hardware orientation, currently employed tools and equipment such as cages, carts, ladders, grounds and bonds, jumpers, aerial devices, and other related items. With the availability of a

jumper clamp that could be installed with the line energized and one that would carry currents of 1,200 amperes, the problem of opening a current carrying connection of item was solved.

Hardware orientation has been specified in all construction specifications for over ten years. These specifications include the requirement that sockets be turned down, or toward the ground on deadened or strain insulator strings, pins be positioned with the cotter key hole toward the tower or structure support location, and similar specifications. All of these specifications were reviewed and it is to be noted that they simplify the performance of hot stick work to a great degree.

Visits were made to other utilities, and demonstrations were conducted on the P. E. Co. system by the insulated tool manufacturers to provide information on the items available and the recommended work techniques. Each point was evaluated by the Company in conjunction with the existing training and work practices. A program for training was drafted in 1964, reviewed again in 1965, and placed in effect in 1966. From 1965 to 1966 all necessary tools and equipment were purchased or manufactured, and the basic items necessary were available at the start of the training.

C. ORIENTATION OF PERSONNEL:

Personnel were orientated in insulated tool work techniques during a six week period. Movies of actual jobs, visits to other utilities, and laboratory demonstrations and tests were conducted on the Company property. Slides were taken of job performance of other utility companies. Our appreciation is extended to the others for their assistance in this respect.

Probably the most important point considered in all the investigations concerned was the possibility of "fear" in the mind of the lineman who would be called upon to do the work. Extensive study was directed to provide ways that this could be dispelled. The linemen themselves actually provided the answers to this possible problem. "Show me" what happens - and then I too will be a believer!

From this study was developed the laboratory demonstration that is outlined in Appendix II. By going over each of the possible happenings from a failure of equipment in the field, and showing what is inherent in the insulated tool work methods they would be asked to employ, the men developed confidence in the methods.

A very important fact that was demonstrated in the laboratory was the need to check the condition of insulators before and after all work. The apparently "good" insulator - one not broken - may actually be defective, since it is possible to have an internally punctured insulator in a string. The use of the Live Line insulator tester permits the determination of the string's condition prior to the performance of any work. (See also Figure IV-13).

A brief outline of the actual practices followed in ascertaining whether it is safe to work on or near a string of insulators is included in Appendix II. Forms are supplied to the crews for plotting the readings taken. Figure IV-11 shows the single prong tester being employed to check an insulator in a deadend string.

The bare hand concept was to be included as a final part of the laboratory demonstrations on insulated tool work using the stick (hot stick work) initially, but the interest of personnel advanced the accomplishment of this Phase of the training so that it was included in the initial demonstrations. It might be said that the students ran ahead of the instructor!

The Safety Department and the Methods and Training Division of the Company were included in all planning and concept development. Their advice and suggestions have been appreciated by the Section. Appendix III outlines some of the considerations evaluated in planning the training program.

D. IMPLEMENTATION:

Since the lineman had actually participated in the development of the entire Program, and had been orientated and informed of the proposed techniques, they were receptive to the conversion to the new work techniques. The detailed studies have provided answers to all questions raised, and the men have been provided with the necessary tools and equipment at the start to permit the employment of the techniques.

As an example, the need for devices to discharge the individual, or prevent the accumulation of the annoying static charge and leakage current build-up on the workman was recognized. These devices, known as static reduction equipment, are part of the tools furnished the lineman. He is taught what charging current is; that it is present whether sticks are used or the bare hand technique employed. With the high load current present on the transmission system, even at 132 kv, static reduction equipment, such as conducting sole shoes, leg-stats, etc., must be employed to discharge the lineman and eliminate the annoying tickle felt when he is discharged or touches a metallic object that may or may not be charged.

The Program or Manual to be used in conducting the training, and the initial essential items of information necessary to establish work rules and guides were distributed to the personnel of the Section early in 1966. After distribution, several classes were conducted where the new concepts were reviewed, questions answered, and areas that were not clear or covered in sufficient detail developed. Hence there was a six-month period of more intensive study by the personnel, and supervision, of the new concepts and techniques.

Also, during this same six-month period, the Insulated Tool Work training yard was constructed. This yard has four basic structures, and is so built that typical types

of construction of the most common types found on the transmission system would be available for the training of personnel, and later the practicing of the techniques developed. Furthermore, the yard would also provide an area where developmental work could be carried out without the necessity of taking a line out of service, or travelling a great distance.

The basic yard included a steel lattice tower, a single wood pole, steel column, and a wood H-frame structure. Four sizes of wire were run as conductors, and the hardware assemblies installed were such that the most general assembly, more difficult to work assembly, and the normal line tensions could be used during the training sessions. Thus any one location on the structure was a typical field condition, even to the sag in the conductor.

With a view toward the future, the conductors were all insulated so that they could be energized at 69 KV for bare hand training using a test transformer.

In addition, a "Kiddie Yard" was built. This yard is used to show closeup the installation of tools, methods of installing armor rods, tying wire, and similar operations. The conductors are near ground level, and the man can stand on the ground and practice the necessary unit work procedure. Skill and practice in the work is accomplished without the necessity of climbing and working from a high structure.

The "Kiddie Yard" also provides an excellent location for the development of specialized tools and equipment. Old or field-hardware assemblies and structure configurations can be mounted at ground level, and the assurance of fit of the insulated tools, safe handling techniques, and other necessary development work conducted prior to the performance of a job in the field.

Adjacent to the "Kiddie Yard" is a storage yard where sample sets of all hardware and other assemblies are stored. Thus, there is available a set of just about every assembly, with the condition of the assembly (rust, worn pins, frozen nuts, etc.) that can be installed in the "Kiddie Yard", and the work requirements determined. This permits the adoption or modification or development of the tools that will be needed to remove the older type assembly prior to the actual job in the field. An attempt is made to maintain a "stock" of every old type assembly for trial and practice use.

E. CONCEPT OF TRAINING:

The previous training given to personnel in the O. H. T. Section emphasized the "Unit Work Concept." Under this concept, the personnel are taught the individual building blocks that may be assembled into a complete job accomplishment. All previous training emphasized this concept; lineman were not taught the step-by-step procedure to accomplish any one job. Training provided the what, where, when and,

most important, the why of the unit work practice. Thus the man knew the why and could judge its applicability to a specific work need. He was always trained to think!

The training itself was conducted using the school-room approach, where there was one instructor or professor, and the men were students. Classes were held with this concept in mind at all times. The only individual present during the actual training were representatives of the Safety, and Methods and Training Departments. When it was necessary to present a briefing to others concerning some Phase of the training program, these presentations were conducted by a selected group after the training of the individuals. Outside observers were not permitted to be present during the actual training sessions, in the same way that visitors are not permitted in the school classroom.

Complete notes were taken of the performance of the individuals during the conduct of the training sessions. Prior to this, the trainees had been notified that this would take place; it was explained that this information would be used to prepare the final Manual for the work, and to provide data for the critique of the Group's training. A tape recorder was also employed to permit the transcription of the lectures, instructions and briefings presented to the Groups. This material provides excellent data for the final text material, and also enables the instructor(s) to determine that the same points are covered in each class presentation.

In addition, Polaroid photographs were taken of the step-by-step performance to permit the explanation of the good or correct methods and also the poor ways of performing a unit work procedure. Thus visual aids may be utilized in the final Manual.

A portable amplifying system is used during all instruction and also by the crews when performing work in the field where experiences or conditions make it difficult to communicate from structure top to ground. (Figure IV-12). A whistle is furnished all crew members to serve as a warning that there exists some hazard; when it is blown, all personnel "freeze" until instructions are issued concerning the correction of the hazard.

Experience has also proven the value of not providing the students with a composite step-by-step procedure for the individual yard practice and training jobs. An outline that provides a method of accomplishing the desired task, and, at the same time, should teach the necessary concepts, was included in the Manual distributed early in 1966. In this way the students attempted to complete the task using the information available, and in accordance with their interpretation of the safety rules and practices, related them to the specific task or unit work procedure. As the students progressed through the procedure, the instructor directed their efforts, as necessary, and corrected mistakes immediately. At times they were permitted to deviate from the expected performance method to illustrate the wrong way of performing the job.

This technique made it possible to have the students do most jobs the "hard way". In some instances, they were directed toward the performance of the work in this manner to illustrate some of the possible pitfalls that may be encountered in actual field work. Thus, they might not be permitted to use a wedge or pry-type cotter key puller to remove a cotter key, even though this would be the normal tool used in this case. The spring loaded puller could accomplish the task, although it required the exact positioning of the tool. Thus the successful student or group found that there is a right and wrong way to use the specific tool or rigging procedure, and this point was driven home to them by actual experience in the training yard.

The final part of Phase I training involved actual work on an energized 220 KV tower, where the personnel were required to replace the entire hardware assembly with the line still in service. This experience permitted correlation with the laboratory demonstrations, training yard use of tools, and the sensations produced by induced charge while in the field of an energized transmission line. The need for conducting sole shoes and other static reduction devices was demonstrated, and the variations between individuals and in the case of the same individual when wearing various types of clothing, in reference to the amount of charge received was illustrated.

Phase IV training involves the bare hand concept. At the training yard, a bare hand platform was erected, and the line energized at 69 KV to permit training on a field structure. (Figure IV-13 and 14). Work and training has included the development of a universal cart, equipped with removable shielding panels, that may be supported from an insulated ladder or similar device. (Figure IV-15 and 16).

F. JOB PRACTICES:

No formal step-by-step procedures have been or will be prepared for the performance of insulated tool work. As mentioned, all lineman training conducted by the Overhead Transmission Section is based on the unit work concept, or the building block approach. Hence, the men are expected to, and do look upon each individual job, be it a simple insulator change or the replacement of a complete structure, as a challenge and a chance to employ the fundamental techniques taught to complete the work safely.

This training and work concept is necessary on the P. E. Co. transmission system due to the wide diversity of structures and wire sizes, and the range of tensions and loadings that may be encountered. To prepare detailed instructions for each entire job would be virtually impossible, and accomplish no useful purpose, except to remove any incentive to think and make sound judgement concerning the work methods to be followed. Also, the individual's pride in thinking a job through in detail would be lost.

CHAPTER H

TOOLS AND EQUIPMENT

A. TOOL LISTS:

Complete tool lists were prepared for the hot stick trailers, and the linemen participated in the identification and stocking of the trailers. This gave them the opportunity to become familiar with the tools and equipment prior to their reporting to the Training Yard. Tools are carried in three basic sets:

1. Wood tool trailer, which has the basic items for a wood pole job;

2. Steel tool trailer, which is equipped with the essential tools and rigging equipment for work on steel structures; and

3. Van trailer.

The van trailer is stocked with the specialized tools and long poles necessary in some instances, and is also provided with a work area to permit the building of specialized tools that may be found necessary in specific cases. The van trailer is of the 5-th wheel type and moved to the job site when necessary behind a tractor. It is approximately 30 foot long, and also equipped with heaters to keep the tools and rope dry. (Figure IV-17.)

B. LINE TRUCK AND PICK-UP TYPE TRUCK:

Details of the line truck and pick-up type truck used by the insulated tool work crews will not be covered in this presentation; further details may be found in the Paper to be made available in July, 1967 (see Introduction). (Figure IV-18.)

C. SPECIALIZED EQUIPMENT ITEMS:

Many items of tools and equipment have been developed and put into use to simplify the work of the crews. They include a rigging board, load calculation sets (drafting equipment, charts, loading data, etc.), special tools for lifting insulators and position plate yokes, pivot type milking tool (Figure IV-19), holder for emery cloth, adjustable wedge cotter key puller, handline hook gauge to check for overloaded hooks (Figure IV-20), and many others.

Illustrations of their use will be found in the paper referred to in the Introduction.

A very important auxiliary item incorporated into the training involved the use of aperture cards and the associated capability of having prints and other data concerning the actual field structure available for the crew's use. Aperture card records of drawings and photographs of each transmission structure are available to the men at the office and permit the preliminary evaluation of the job before they leave for the field. Hence, specialized tools or equipment can be loaded, accessibility of the structure determined, and the tensions and mechanical loads they may encounter calculated, including clearance dimensions. Scaling from drawings permits the plotting of the loads using simple force diagrams. In conjunction with the rigging board, full model job procedures can be portrayed, and the loads measured on the board to see that the selected rigging equipment will not be overloaded or clearance rules violated.

It is impossible to list or include all the individual tools, equipment or training aids that have been employed by the Section in conducting the training and work on energized lines. More examples will be included in the Paper cited in the Introduction.

CHAPTER I

ACTUAL JOB EXAMPLES

The Section has performed many different jobs since the completion of the basic phases of the training. Although it might be anticipated that most of the work would involve the replacement of damaged insulators, this has not been the case in the Company. Damaged insulator replacement has only required about 5% of the time of the personnel engaged in energized line work maintenance.

Most of the jobs that have been accomplished have resulted from the requirement to maintain a line in service, while still accomplishing a maintenance or construction operation.

Some examples of the work done are as follows; they are not described in detail in this Paper, but may be found in the paper cited in the Introduction:

A. REMOVE WAVE TRAP:

On a 69 KV line at the substation terminal, it was necessary to remove a wave trap from the line and rebuild it so it could be installed at another location. The trap was jumpered, the 795 mcm ACSR wire cut and leads removed, and the trap relocated while the 69 KV line was carrying approximately 50 MW of load.

A hydraulic cable cutter was employed to cut the ACSR conductor. It was powered with a portable 12-volt battery pump, which was moved to the cut location using insulated tools. The electric switch to actuate the pump was operated with a tool stick. It is believed that this is the first time wire of this size was cut with the line energized using only hot sticks. (Fig. IV-21).

B. PLACE LINE CONDUCTOR IN RUNNING BLOCKS:

The conductors on a 69 KV line had to be relocated. Since the line could not be taken out of service except on a Sunday, and the scope of the work was such that the entire job could not be accomplished in one interruption without extensive temporary construction, the line's conductors were placed in running blocks, and the lower crossarm removed from the single pole structures using insulated tools prior to the Sunday interruption.

This enabled the line crews to complete the work requiring the Sunday interruption on one Sunday, and without any temporary construction.

C. PHASE IDENTIFICATION:

In conjunction with the placement of a new generating facility in service, it was necessary to identify the phases at the station. A 220 KV test voltage was sent to the station, one phase at a time, from the location where the new 220 KV line was T-tapped to an existing line. The connections were made with insulated tools. Had it been necessary to block and ground the 220 KV line, the job would have required over 6 hours. With insulated tools, the phase identification was completed in two hours.

D. DEVELOPMENT CREW:

One crew of men is generally engaged in planning and developing new tools and work techniques at all times. They are split, as necessary, and accomplish a wide variety of tasks including new specialized tools, determination of a practical method to accomplish a new job or task, revision of existing methods, and many other activities.

The development personnel are also engaged in implementing all the concepts and methods available to accomplish the work; they are not restricted to hot stick work only. Hence, the bare hand technique, in combination with the hot stick, is considered as one entire concept of work accomplishment, and treated as such. The method selected is generally a combination of hot stick and bare hand work in many cases; the best and most efficient being the one actually employed in the job.

CHAPTER J

THE FUTURE

The future of energized line maintenance on the P. E Co. transmission system seems to be limited only by the availability of jobs and the time to complete the development of the necessary tools and equipment. The basic knowledge to accomplish almost any job is available, and the combination of the best technique permits the successful completion of a job.

Our enthusiasm for the bare hand and hot stick methods is really boundless, and cannot be adequately expressed in a Paper of this type. Espirit de Corps of all personnel seems unmeasurable and has exceeded expectations. This extends through the Chairman of the Board, who has also become a member of the "P. E. CO. Bird-on-the-Wire Club."

Costs, overtime, interruptions all have been reduced, while pride in their work has raised the spirit of the crews. Safety is still primary, and we feel the hazard, such as it is, of doing line work by any method has been reduced.

APPENDIX I

INSULATED TOOL WORK TRAINING PROGRAM
COURSE CONTENT AND HOURS

May 1, 1967

The training of personnel of the Overhead Transmission Section in the employment of Insulated Tools follows the basic course content listed below. Cognizance must be taken that this training program follows after the instructional material given to these personnel during their previous training periods in the Section, and hence certain fundamental concepts are already routine practice.

As an example, the word "bond" and the fact that a "bond" must be installed at the work location during any de-energized work has been made a matter of routine practice by the personnel in the Section, and is not included in this block of instruction.

A. SUMMARY OF TRAINING:

Training conducted in Insulated Tool Work practices, methods, and procedures, after a lineman completes progression to Lineman, First Class, Overhead Transmission, and has received basic orientation on aerial devices, rigging, nylon slings, etc.:

CONTENT SUMMARY	HOURS (See *NOTE at end)
1. Pre-Training Briefings	Approx. 6 hours
2. Introduction to Entire Program	4 hours
3. Phase I - Insulated Tool Employment from a Structure	55-1/2 hours
4. Phase II - Insulated Tool Employment from an Aerial Lift (Not Insulated) (a) Basic Training (13 hours) (b) Refresher Training (8 to 24 hours; average 16 hours)	19 hours
5. Phase III - Insulated Tool Employment from an Aerial Lift (Insulated - "Bare-hand")	30 hours
6. Phase IV - Insulated Tool Employment from Various Insulated Supporting Devices (Various "Bare-hand" Concepts)	28 hours

CONTENT SUMMARY	HOURS (See *NOTE at end)
7. Continued Development of Procedures Involving Insulated Tools	(At least 1/2 hour per month, plus development time; continual requirement)
TOTAL TRAINING HOURS	142-1/2 hours *

B. DETAILED INSULATED TOOL WORK TRAINING SCHEDULE:

(Based on Training of Group III in Fall, 1966 (13 Trainees and 4 Instructors)

Par.	Procedure - Instruction	"Reference" Material	Time
1	Pre-Training Briefings:- (Movies, talks, etc.) (Conference Room at Service Building)	Manual, Lineman's Handbook, Methods Manual, Previous Instructional Material	(Approx. 6 hrs. over a 2 year period prior to start of Phase I Training
		TOTAL Par. 1	Approx. 6 hours
2	Introduction to Entire Program:-		
	a. Distribute "Manual" (Conference Room - Individuals Read at Home)	Manual	1 hour
	b. Discuss Manual (Conference Room)	Manual	(About 1 hour)
	c. Electrical Principles - Laboratory Demonstration (At Electrical Laboratory)	TAB D	
	d. Training Yard Orientation (Visit to yard site)	TAB E	(2 hours)
		TOTAL Par. 2	4 hours

*NOTE: Time for any particular block of instruction will vary depending on progress of the class, weather, availability of lines and equipment for practice, etc. In each block, the instruction shall cover all points, and all students shall become knowledgeable in the subject matter before proceeding to the next block of instruction.

Par.	Procedure - Instruction	"Reference" Material	Time
3	Phase I Training - Insulated Tool Employment from a Structure:- (Use of Insulated Tools)	TAB F	
	a. Classroom Orientation prior to start of yard tool work training (Conference room at Service Bldg.)	TABs A thru D and H thru L	2-1/2 hours
	b. Yard Training-Orientation at Yard (Structures, loads, tools, wire sizes, etc.)	TABs F and G	1-1/2 hours
	c. Procedure F - I (Str. B) (Change Insulators on 132 KV-Class Deadend Lattice Tower)	TAB F-1	8 hours
	d. Procedure F-2 (Str. A) (Remove & re-tie 66 KV post insulator; tighten eye bolt; remove wire from strut insulator clamp; change insulators and clamp on suspension string) (Single wood pole 66/132 KV-class structure)	TAB F-2	9 hours
	e. Procedure F-3 (Str. D) (Support conductors deadended on arms by various methods; replace crossarms on structure) (Wood H-Frame double arm 132 KV-Class deadend structure)	TAB F-3	12 hours
	f. Procedure F-5 (220 KV Suspension Tower; Line De-energized) (Remove old hardware, clamp, insulators, armor rods and install new modern assembly) (220 KV-class single string suspension tower; Line de-energized)	TAB F-5	5 hours
	g. Procedure F-5 (Modified) (220 KV Angle Suspension Tower - Hard angle; Line De-energized) (Remove old hardware, clamp, insulators, armor rods, and install new modern assembly) (220 KV-class angle double string suspension tower; Line de-energized)	TAB F-5	5 hours

Par.	Procedure - Instruction	"Reference" Material	Time
	h. Procedure F-5 (220 KV Suspension Tower; Line energized)		
	(1) Orientation before Start of Job	TAB F-5 and Notes	1 hour
	(2) Replace insulators and suspension clamp. (Line energized) (Single string tangent 220 KV suspension tower; Line Energized)	TAB F-5	4 hours
	i. Critique of Training Review of all previous training in classroom	(Notes)	3-1/2 hours
	j. Practice Sessions (Field work on actual lines, etc.)		
	(1) Armor Rod Conductors (At "Kiddie" Practice Yard)	(Notes)	1 hour
	(2) Land and handle deadend tool yokes (At "Kiddie" Practice Yard)	(Notes)	1 hour
	(3) Change single string 69 KV suspension insulators on live tower	(Notes)	2 hours
4	Phase II - Insulated Tool Employment from an Aerial Lift - Not Insulated:- (Use of an Aerial Bucket as work platform)		
	a. Orientation in classroom	(Notes)	1 hour
	b. Field work - change insulators on a 69 KV suspension tower using aerial bucket	(Notes)	4 hours
	c. Field work - change arms and hardware on 66 KV single wood pole suspension structure	(Notes)	8 hours

Par.	Procedure - Instruction	"Reference" Material	Time
5	Refresher Training:- (Conducted as necessary. Personnel use training yard and/or actual line structures to develop work techniques)	(Notes and Actual Job Requirements)	(8 to 24 hours)
6	Phase III - Insulated Tool Employment from an Aerial Lift - Insulated:- (Use of an aerial bucket in "bare-hand" work)		
	a. Orientation in Classroom	(Notes)	2 hours
	b. Review of Aerial Device Operating Rules and Instructions (Classroom and Field)	Operating Rules	1 hour
	c. Review of Electrical principles involved; Electrical requirements of aerial device (Classroom and Field)	Electrical Principles Course	1 hour
	d. Procedure - Replace Insulators on Suspension structure (Field)	TAB III-A	8 hours
	e. Procedure - Handle "hot" end of Job involving replacement insulators on 132 KV deadend structure - "cold" end work by sticks (Field)	TAB III-B	8 hours
	f. Procedure - Install armor rods over damaged wire strands (Field)	TAB III-C	4 hours
	g. Procedure - Install full tension compression joint in line wire carrying full load current (220 KV line) (Field)	TAB III-D	4 hours
	h. Critique of all work and Review of Methods and Practices (Classroom)	(Notes)	2 hours

Par.	Procedure - Instruction	"Reference" Material	Time
7	Phase IV - Insulated Tool Employment from Various Insulated Supporting Devices - "Bare-hand" Methods:-		
	a. Orientation in classroom Explain again principles; illustrate and show various concepts including: (1) Reaching energized part from and with a ladder (2) Use of Insulated platform (3) Use of cart and/or cages (4) Shielding requirements (5) Conducting suits and related devices (6) Rigging; insert insulating devices in rigging	TAB IV	3 hours
	b. Thru ? - Procedures involving actual field jobs (Exact procedure depends on the jobs to be performed at the time training is conducted) (1) Each "Job" is practiced in a "dry-run" at the Training Yard prior to first field performance. (2) After rehearsal, the job is performed in the field on actual structures	(Prepared for the Procedures)	Total 24 hours
	c. Critique in Classroom (Conducted as required during course of all work operations and Procedures)	(Notes)	1 hour (additional time when required)
8	Continued Development:- There exists a requirement for continued review and development necessitated by: (1) New job requirements (2) Better construction techniques	(Field Performance Reports; Jobs; Notes)	(At least 1/2 hr. per month)

Par.	Procedure - Instruction	"Reference" Material	Time

(3) New Equipment and Tools

(4) Refresher training to point out any techniques that should be changed, etc.

Hence, training of this nature is continual. At least once per month 1/2 hour is devoted to a review of the above with all personnel.

General Notes:

1. When the word "notes" is indicated under "Reference" Material, it is understood that the material is an extract of all previous material, and additional material developed for the particular situation.

2. TABs are the sections of the current Insulated Tool Work Manual published by the Overhead Transmission Section; this Manual is not complete, or in final form, as of this date.

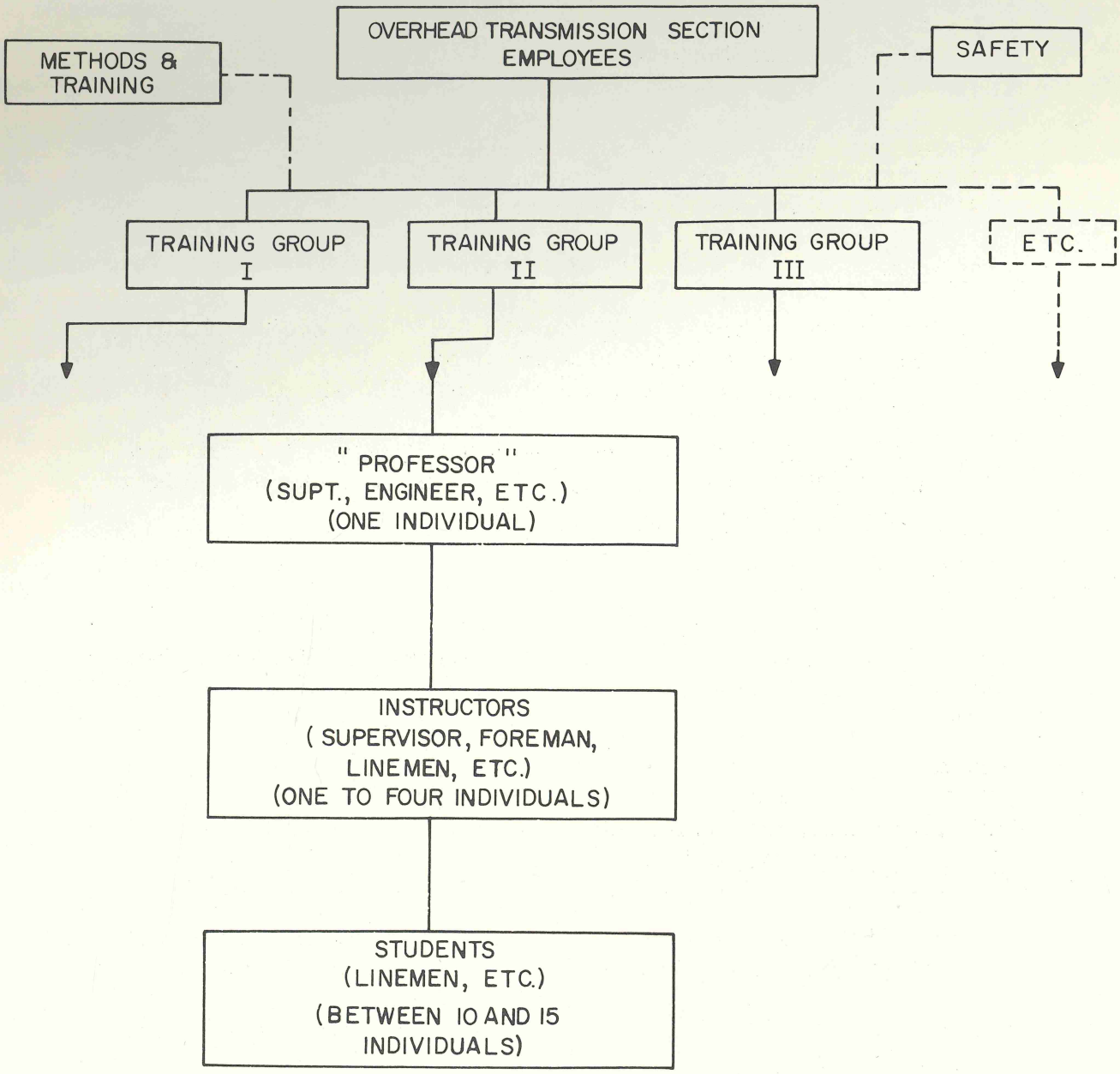
Overhead Transmission Section
May 1, 1967

Attachment:

Encl. I - Training Organization Chart
dated May 1, 1967

Training Organization Chart

May 1, 1967



Overhead Transmission Section
May 1, 1967

(Enclosure 1 to Appendix I)

APPENDIX II

INSULATED TOOL WORK TRAINING SCHEDULE

BRIEF OUTLINE OF LABORATORY DEMONSTRATIONS

May 2, 1967

The Insulated Tool Work Training Program of the Philadelphia Electric Company includes a series of demonstrations conducted at locations where required electrical and other laboratory facilities are available. Below is an outline of typical material included during the Phase I training on the employment of insulated tools (hot sticks) from a structure or platform, and the introduction of the live line (bare hand) technique. Demonstrations of this type were presented to management and other interested groups to inform them on the training program.

The outline does not include all points mentioned or demonstrated during this training; full coverage is included in the reference paper mentioned in Chapter A, Introduction.

Below is the anticipated lesson plan for the Brief Outline Demonstration to be conducted for the Section Personnel at the Fifth Floor Testing Laboratory, 2301 Market Street in 1966.

A. OUTLINE OF PROGRAM:

1. Appreciation to the management of the Philadelphia Electric Company.

   a. Number of years in development: Adoption of entire concept of work: "Insulated Tool Work" - actually practiced for a long period of time.

   b. Really four (4) types of methods of doing work on a transmission line:

      (1) Insulated Tool Work - "Hot Stick" work.

      (2) "Bare Hand"

      (3) De-energized work

      (4) Combination thereof

2. Program developed to include the following: Phases of training for the Overhead Transmission Section.

   a. Phases: I - Insulated tools from a structure.

      II - Insulated tool work from a bucket. (Bucket not insulated)

      III - Insulated tool work from a bucket. (Bucket insulated)

      IV - "Bare-hand" method (from insulated platform, or other supporting means)

   b. Program and training started August 29, 1966. Program Schedules and Manuals for Phase I were distributed in March of 1966.

3. Description of Program:

   a. Orientation - Movies of work. Presented to Foremen over a period of five (5) years; to Linemen prior to the beginning of the actual field training.

   b. Details of Phase #1 Training.

      Phase I - Insulated tool work from a structure, involves eight (8) sessions.

         Session 1 - Electrical Demonstration, as presented in this laboratory (TAB D).

         Sessions 2 thru 7 - Involves Yard Training in "Unit Work Procedures".

         Session 8 - Involves Field Work Training as a crew.

      Phase II - Insulated tool work from bucket or platform with tools or under de-energized work conditions will be conducted, starting about October 15, 1966. The boom of the bucket will not be insulated at this time.

      Phase III - Bucket/platform work - "Bare-hand" This work is expected to commence on/about December 1, 1966.

      Phase IV - "Bare-hand" using all means of support can be performed at any time, basic tools and needed equipment, including all techniques, is available.

   c. The objective of the entire program is the training in combining of all of the methods or techniques of work. The actual work-method employed will be combination(s) of those most practical for the particular job.

4. Training Concepts:

a. Personnel of the O.H.T. Section divided into three (3) Groups of 11 to 15 men each.

b. All in one class, or in individual classes and/or sections.

c. Refresher training, and repeat of previous parts or sessions of any phase, to be conducted as necessary.

d. All training of personnel in the O.H.T. Section to be conducted based on the "Schoolroom" concept, where there is only one teacher for the students. Observers from Methods and Training, and Safety to be present at all sessions.

5. Present Status:

a. Rapid advance. Demonstration - Introduced the "bare-hand" technique - All personnel of this Section participated in the demonstration.

b. Show/explain all points of the work - eliminate "fear".

c. Prior planning resulted in having all basic tools/equipment ready. Answers to all questions appear to be available, because of detailed previous investigation.

d. Although not completely printed in a Manual, all the concepts were/are available. The rate of teaching actually is following the rate of advance of the classes, which is rapid. Recordings were taken of the sessions in order to obtain complete lesson material. Repeat of any section or lesson may be made when necessary. Each group or individual in this Section to pass same "Exam". Repeat, if necessary, any or all the training material.

e. Personnel participated in the training, and, as appropriate, assisted in the development of the training material, concepts used, and in the conduct of the training.

f. Emphasized then, and now, that these procedures and practices are applicable to "Transmission". In preparation is a Manual titled: "Manual of Overhead Transmission Practices".

g. Demonstrations and instructions show "minimums". Emphasized that they are minimums.

h. Explanations given of the EEI Accident Report-fatalities used to emphasize the points.

i. Thru films and field training, emphasized that the Philadelphia Electric Company adopted the best points of all the methods practiced by others.

6. Certain New Terms Defined:

a. "Insulated Tool Work".

b. "Bond", "Jumper", "Shunt"; "Ground"; "Potential", "Voltage"; "Static Charge". New Operating terms: "Permit", "Restriction".

c. "Safe" work - Safety or "safe" versus "hazard" defined. Emphasize three (3) "factors of safety" included in all work practices or methods.

7. "Teaching" Method:

a. Class versus demonstration.

b. Present in the class or for class training: Safety, Methods and Training, one observer from engineering. During demonstrations, other interested individuals were present.

c. Laboratory participation. Appreciation to laboratory personnel and development of this demonstration.

d. Record made of actions - photographs taken of actual work procedures.

e. Demonstration proved that it was an excellent training vehicle to emphasize proper existing "Methods" (those previously used with de-energized work techniques).

8. This Demonstration:

Listed is a brief outline of the Insulated Tool Work electrical demonstration to be conducted as a briefing on this Phase of the Insulated Tool Work Training.

A detailed outline and explanation is included in a separate Memorandum (TAB D-a).

B. OUTLINE OF ELECTRICAL DEMONSTRATION:

1. Voltages:

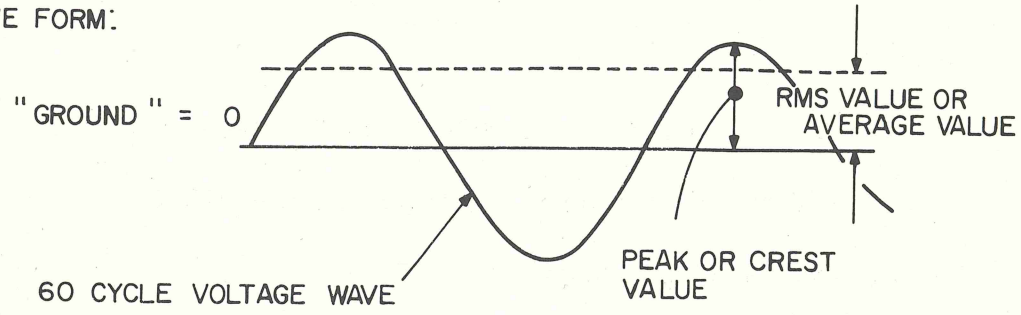
The following Table of Voltages for operating lines on the Philadelphia Electric system is furnished to provide a means of comparing the demonstration results with field conditions. Voltages are approximate; that is, within the tolerances observed by field forces.

TABLE D-b1

Voltages on P. E. Co. System

"Nominal" Phase to Phase or Line to Line (rms)	Phase to Ground (Actual Voltage) (rms)	Plus 10% for Over-voltage (rms)	Peak Maximum Voltage	Surge Factor (Examples)	Crest KV Maximum Any time from 60 cycle Power Voltage	Approx. Rod gap Flashover Voltage 60 cycle Peak
33 KV	20 KV	22 KV	31.1 KV	2.6	81 KV	0.26 ft. (3.1 in.)
66 KV	40 KV	44 KV	62.3 KV	2.6	162 KV	0.87 ft. (10-1/2 in.)
132 KV	79.6 KV	87.5 KV	124 KV	2.6	323 KV	2 ft.
230 KV	133 KV	146 KV	207 KV	2.6	538 KV	3-1/4 ft.
500 KV	289 KV	318 KV	450 KV	2.2	990 KV	6-1/4 ft.

VOLTAGE WAVE FORM:



2. Flashover Distances.

a. General - Demonstrations

Conducting Object	Distance	Expected Flashover Voltage	
(1) Sphere Gaps	7.5 cm/2.95"	140 KV	
(2) Plate Gaps	7.5 cm/2.95"	60 KV	
(3) Rod to Plate Gap	7.5 cm/2.95"	40 KV	
(4) Rod to Rod Gap	7.5 cm/2.95"	48 KV	
(5) Rod to Rod Gap	10 3/4"	100 KV	(Between rungs of an Epoxiglas ladder)

b. Other illustrations

(1) Change in voltage

(2) Electrical characteristic of Epoxiglas ladder

3. Voltage (Potential) Characteristics of Insulators:

a. General - Demonstrations

(1) 5 - 10" Suspension insulators - all good. 150 KV - no flashover. Measure leakage with R. and I.E. Tester (Live Line insulator tester, now manufactured by the I.T.E. Company).

(2) 5 - 10" Suspension insulators - all good 75 KV. Plot curve of leakage using data from R. and I. E. Tester.

(3) 5 - 10" Suspension insulators - One defective (#3 or middle one). 75 KV. Plot curve of leakage using data from R. and I. E. Tester.

b. Illustrations

(1) Use of R. and I.E. Tester - determine "good" insulators.

(2) Voltage distribution on and in an insulator string.

(3) Safe handling of tester.

(4) Plotting of "curve" to show voltage distribution in string (TAB D-b1 attached)

4. Insulator String Flashover:

a. General - Demonstrations

(1) 5 - 10" suspension insulators - all good. No flashover at 150 KV.

(2) Corona at end of pipe simulating line conductor or sharp object. 150 KV.

(3) 5 - 10" suspension insulators - Units 1, 2, 4 and 5 defective (bad); Unit #3 (middle) good. Flashover at 110 KV (illustrate "Thomas" case of defective insulators).

(4) As in (3) above. 5 - 10" suspension insulators - Units 1, 2, 4 and 5 defective (bad); Unit #3 broken (middle unit) "partially" good. Flashover at 84 KV.

(5) As in (3) above, Unit #5 alone. Flashover at 30 KV.

(6) Epoxiglas link stick. 12-inch gap between end metal fittings. Flashover at 127 KV.

(7) As in (3) above (same string), 5 - 10" suspension insulators - Units 1, 2, 4 and 5 defective (bad); Unit #3 (middle unit) is good. (Only good unit in string.) Add link stick so that the metallic portion of stick is next to the skirt of the good #3 unit - the metallic portion of stick "shorts" out the good unit. Flashover at 70 KV.

(8) As in (7) above, 5 - 10" suspension insulators - Units 1, 2, 4 and 5 defective (bad); Unit #3 (middle unit) broken, but "partially" good. (Same broken unit as used in test in paragraph (4) above.) Add link stick so that the metallic portion of the stick is next to the skirt of the broken unit #3 (partially good). Position, if possible, so that metallic portion fits into the "groove" or cracked area of unit and this is closer to the metallic cap and pin of unit. Flashover at 44 KV.

(9) Wet down a string of 5 - 10" suspension insulators that are all good. (String from (1) above). Lower flashover value and time to this value (approximately 130 KV in test of 9/7/66).

(10) Link stick "wet".

b. Illustrates:

(1) Good insulator string.

(2) Corona formed at sharp edge or corner.

(3) Reduction in insulation strength with one defective unit and with 4 defective units.

(4) Appearance is not a firm guide to insulator string insulation strength.

(5) Flashover strength of Epoxiglas.

(6) Metallic parts of insulated tools, when positioned near an insulator, change the insulation strength of a string.

(7) A broken insulator may still have some insulation strength left - a part of original flashover level.

(8) Wetting an insulator string changes the flashover strength of the string.

5. Use of Insulated Tool Tester:

a. General - Demonstrations

(1) Maximum voltage across sphere gaps inside tester is 1300 volts.

(2) Resistance in the small stick that is used as a standard to see that tester is working is 1,030,000 ohms (1.03 megaohms). Gap between metal rings is 5-1/2 inches.

(3) Current (leakage) that the meter reads and indicates "Bad" is 0.001 ampere or 1 milliamp.

(4) If the meter, when used on a stick does not indicate "bad" or "red", stick is good and leakage current low enough.

(5) Check a stick that "looks" bad with the tester. Tester shows "good".

(6) Use same stick as in (5) above and with gaps at 5-1/2" show that it flashes over at 50 KV (5-1/2" or still 100,000 volts or 100 KV per foot).

b. Illustrates

(1) Insulated tool work tester components.

(2) Use of tester and test standard

(3) Tester results agree with the actual laboratory check on a stick.

6. Insulation Strength of Epoxiglas insulated tools:

a. General - Demonstrations:

(1) Test stick with 42 inch gap to 150 KV. No flashover.

(2) Move down stick and shorten gap across stick. No flashover at 150 KV with 18 inch gap.

(3) Flashover when gap approaches 10-inch separation (135 KV).

b. Illustrates:

(1) That Epoxiglas insulated tool strength is about 100,000 volts or 100 KV per foot - length for 60 cycle power voltage flashover.

(2) Compare with link stick flashover. 12" gap flashed over at 127 KV.

7. Comparison of Surge (Lightning/Switching) and Power Arc Follow-up:

a. General - Demonstrations

(1) Charge capacitors and discharge across "door handle" spheres. Charged to 46 KV. Sphere spacing about 2 inches. Note "yellow" arc.

(2) Charge capacitors and then discharge, but with addition of power current from power transformer. Note "blue" arc, and "size" of arc.

(3) Insert wood block with hole that is filled with sawdust. Discharge capacitors only - 46 KV. Sawdust blows out.

(4) Again fill hole in block with sawdust. Charge capacitors and discharge, but add power current from transformer. Sawdust blows out and also catches fire.

b. Illustrates:

(1) Color and magnitude of impulse arc (yellowish) compared to power arc (bluish). Lightning surge or bolt.

(2) Forces set up due to an electrical arc. Thunder in connection with lightning.

(3) Damage that power arc produces. Longer duration and hence more power or force. Breaks insulators, severe wire damage, etc. "Burns" on wire - copper vs. aluminum.

8. Insulated Tool Work from an Insulated Platform (Bucket, Cage):

a. General - Demonstration

(1) Platform on 66 KV class stack type insulators. Copper rod simulates the wire at end of string of 5 - 10" suspension insulators (all good). Metallic plate on platform.

(2) Raise voltage on "wire" to 40 KV (approximately the phase or line to ground voltage on a 66 KV line).

(3) Bond to the wire. Use 6' stick and then shorter stick. Two bonds. Make "buzz" test prior to installation of any load (energized or de-energized).

(4) "Tickle" that can be felt.

(5) Remove bonds and discharge the platform.

(6) Make "buzz" test from platform and from "ground".

(7) Short out a unit - hot end unit. Change voltage distribution on units.

b. Illustrates:

(1) Charging current to platform (2-1/2 ma.) and "man".

(2) Difference in "arc" during buzz test. Use of buzz test each time. Check that object is now "HOT" vs de-energized concept that it is "DEAD".

(3) "Bonding" is really being done in all work practices.

(4) Discharge of platform.

(5) Extend parts of body outside "shield" area. Shielding by any metallic parts at same potential ("voltage"). Difference in potential is important.

(6) Reliability of a "ground" - absolute reading.

(7) Bucket truck - bonding at bucket and at chassis.

(8) First stick used to have proper length of insulation. (6 foot length of "insulation"; obtained from an 8 foot stick.) Need for two bonds.

(9) Use of "conducting" sole shoes and other devices.

(10) Movement of stick head-end beyond the first part of a conducting object; judgement of distance.

(11) "Arc" blindness if too close to the arc.

9. Insulator Voltage Distribution:

a. Pass out copies of Curve (TAB D-b2) showing percent of voltage across each insulator in a string. (Ohio Brass Data). Discuss.

b. Furnish copies of insulation strength of various numbers of insulators in a string. Dry, Wet, 60 cycle, impulse, etc. (Ohio Brass Data). (TAB D-b3).

10. Remarks, Questions, Comments:

(a) Further developments necessary.

(b) (Go over Tab D-b)

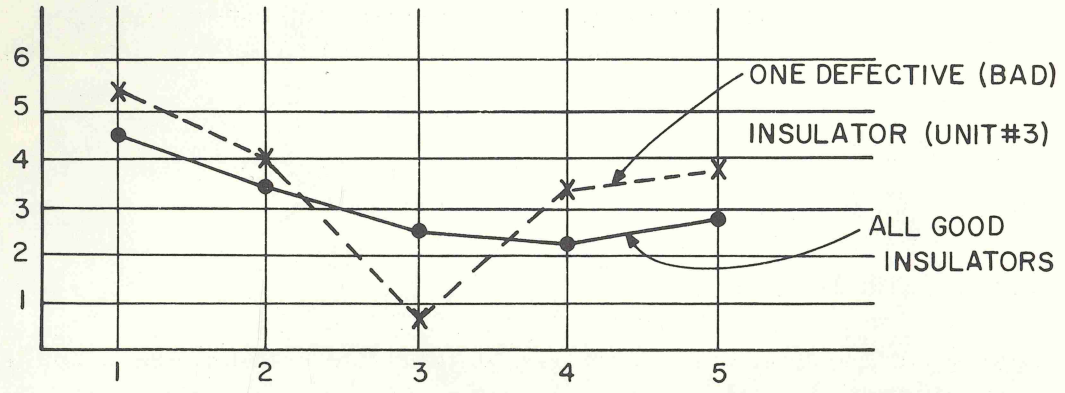
(c) Repeat certain applicable "points". We illustrate in this presentation the major items.

APPENDIX II

TAB D-b1
SAMPLE INSULATOR-R. & I. E.
METER TEST DATA

August 31, 1966

Sample plot of R. and I.E. Test Set meter reading for a particular scale setting obtained under two conditions: (1) All good insulators; (2) One defective (bad) insulator (Internal puncture or short).



Insulator Number (Unit) - From Conductor or "Hot" End of String #1 to "Ground" #5.

Conditions: (1) 5-10" insulators in string

(2) Voltage is 75 KV rms phase to ground. (Slightly higher than 66 KV System peak voltage of 62.3 KV - See Table D-b1).

Prepared by:
Overhead Transmission Section
Philadelphia Electric Company
August 31, 1966

APPENDIX II

TAB D-b2
PERCENT VOLTAGE ON INSULATORS IN A STRING

August 31, 1966

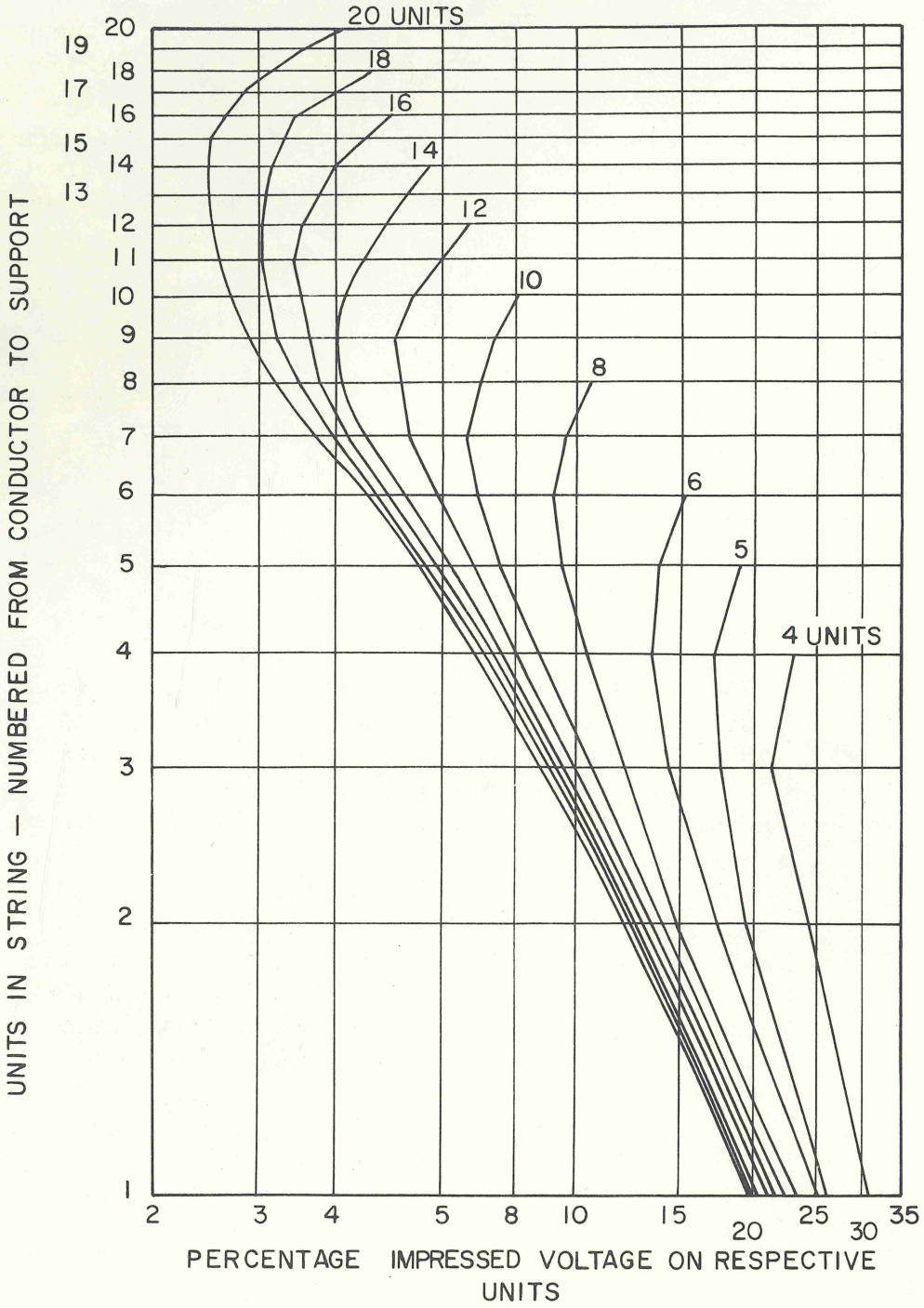
Curves and data illustrating the percent of the voltage impressed or applied to a string of suspension insulators. The curve shows that the insulator nearest the energized part has the highest potential difference across it compared to the other insulators in the string. No shielding present during the obtaining of the data. (From Ohio Brass Company technical data Cat. #31 - page 31-41).

(See table on next page)

Prepared by:
Overhead Transmission Section
Philadelphia Electric Company
August 31, 1966

TAB D-b2

PERCENT VOLTAGE ON INSULATORS IN A STRING



TAB D-b3

FLASHOVER VALUES OF INSULATOR STRINGS

August 31, 1966

Table of data showing flashover values of various lengths (number of units) of suspension insulators in a string, under dry, wet, 60-cycle power and impulse (similar to lightning) conditions. (Ohio Brass Co. Technical Data, Cat. 31, page 31-42).

TABLE D-b3-1

5 3/4 x 10 Inches - Suspension Insulators

No. of Units	60-Cycle Flashover		Impulse Flashover - kv 1-1/2 x 40 micro-sec. (μ-s) wave					
			Positive			Negative		
	Dry	Wet	Critical	4 μ-s	2 μ-s	Critical	4 μ-s	2 μ-s
2	155	90	255	255	295	255	260	285
3	215	130	355	360	425	345	365	415
4	270	170	440	465	555	415	465	535
5	325	215	525	565	685	495	570	665
6	380	255	610	670	815	585	690	800
7	435	295	695	775	945	670	795	925
8	485	335	780	880	1070	760	900	1055
9	540	375	860	985	1195	845	1010	1185
10	590	415	945	1080	1320	930	1115	1310
11	640	455	1025	1175	1430	1015	1220	1425
12	690	490	1105	1270	1545	1105	1325	1555
13	735	525	1185	1370	1665	1190	1420	1680
14	785	565	1265	1465	1780	1275	1525	1805
15	830	600	1345	1560	1890	1360	1630	1925
16	875	635	1425	1660	2010	1440	1735	2050
17	920	670	1505	1755	2125	1530	1840	2170
18	965	705	1585	1850	2245	1615	1940	2295
19	1010	740	1665	1950	2365	1700	2035	2415
20	1055	775	1745	2045	2470	1785	2140	2535

Prepared by:
Overhead Transmission Section
Philadelphia Electric Company
August 31, 1966

APPENDIX III

CONSIDERATIONS IN STUDY OF INSULATED TOOL WORK PRACTICES

The Philadelphia Electric Company devoted much time to the complete study of all phases of insulated tool work practices prior to the adoption of the methods for routine work. These studies encompassed many areas and were accomplished through the assistance and cooperation of many Departments and Divisions within and outside the Company.

An outline of some of the areas studied follows:

1. Safety.

    a. Insulated tool work would eliminate some of the hazards present in performing line work.

    b. Related factors.

        (1) Obtain adequate equipment.

        (2) Provide complete and thorough training.

        (3) Develop work rule and individual unit work practices.

2. Equipment is a major factor in performance.

    a. Accept industry standards with respect to hazards involved.

    b. Statistics prove that there would be less hazard under the insulated tool work concept, due to the built-in hazard reduction factors, than would normally be encountered in driving a car or climbing a flight of stairs.

    c. It is possible to develop and employ safe equipment.

    d. The greatest hazard is human failure.

3. Questions to be answered.

   a. The personal characteristics of men who will perform insulated tool work.

   b. How to train the personnel involved.

   c. Number of personnel to be trained.

   d. Change from previously employed methods and its effect.

   e. How to develop safety rules and practices.

   f. Limitation of the work techniques to the transmission system at present.

   g. Establish set unit work practices.

   h. Care of and testing of all equipment to be employed.

4. Acquired answers over an extended period of time.

   a. Visited vendor's plants and laboratories where equipment and tools were tested.

   b. Personnel volunteered for the work without specific selection. All personnel were trained.

   c. The necessity to develop a "work together" attitude among personnel.

   d. Acceptance of concepts. Discuss early in Safety Meetings and other training sessions. Brief Foreman and linemen early. Request that they think about concepts and ask questions; but supervision must have adequate answers available.

5. Develop training methods.

   (Covered in the main body of this paper).

6. Two greatest hazards in bare hand work.

   a. Contact another voltage or develop a difference of potential across the individual. Solved through the employment of adequate clearances, wherein it is virtually impossible to reach an energized part at different potential.

b. Place the man in series with a conductor carrying current. Solved by maintaining the rule that two bonds shall be installed at the work location and a jumper placed whenever a current carrying connection is to be opened.

7. Summary

a. Each man must understand the electrical principles involved.

b. Personnel taught the unit work procedure or building block. He shall know the WHY of each work operation.

c. Use of the analogy of the water pipe to explain current and voltage, and the "bird on the wire" for the bare hand concept.

d. Continually interject safety, and emphasize that by following the work procedures set forth, a man would have to commit at least three "violations" of safety guides before he may be hurt.

e. Safe and efficient work performance depends on the performance of each individual in the work crew.

APPENDIX IV

MAPS AND FIGURES

May 6, 1967

This Appendix includes a map (Fig. IV-1, Page IV-2) of the area served by the Philadelphia Electric Company, and a Schematic Map showing the lines or circuits of the bulk power Transmission System as of January 1, 1967 (Fig. IV-2, Page IV-3). The Schematic Map does not show all lines maintained by the Overhead Transmission Section.

A limited number of photographs are included to illustrate some points mentioned in the Paper; a complete story will be found in the final paper mentioned in the Introduction.

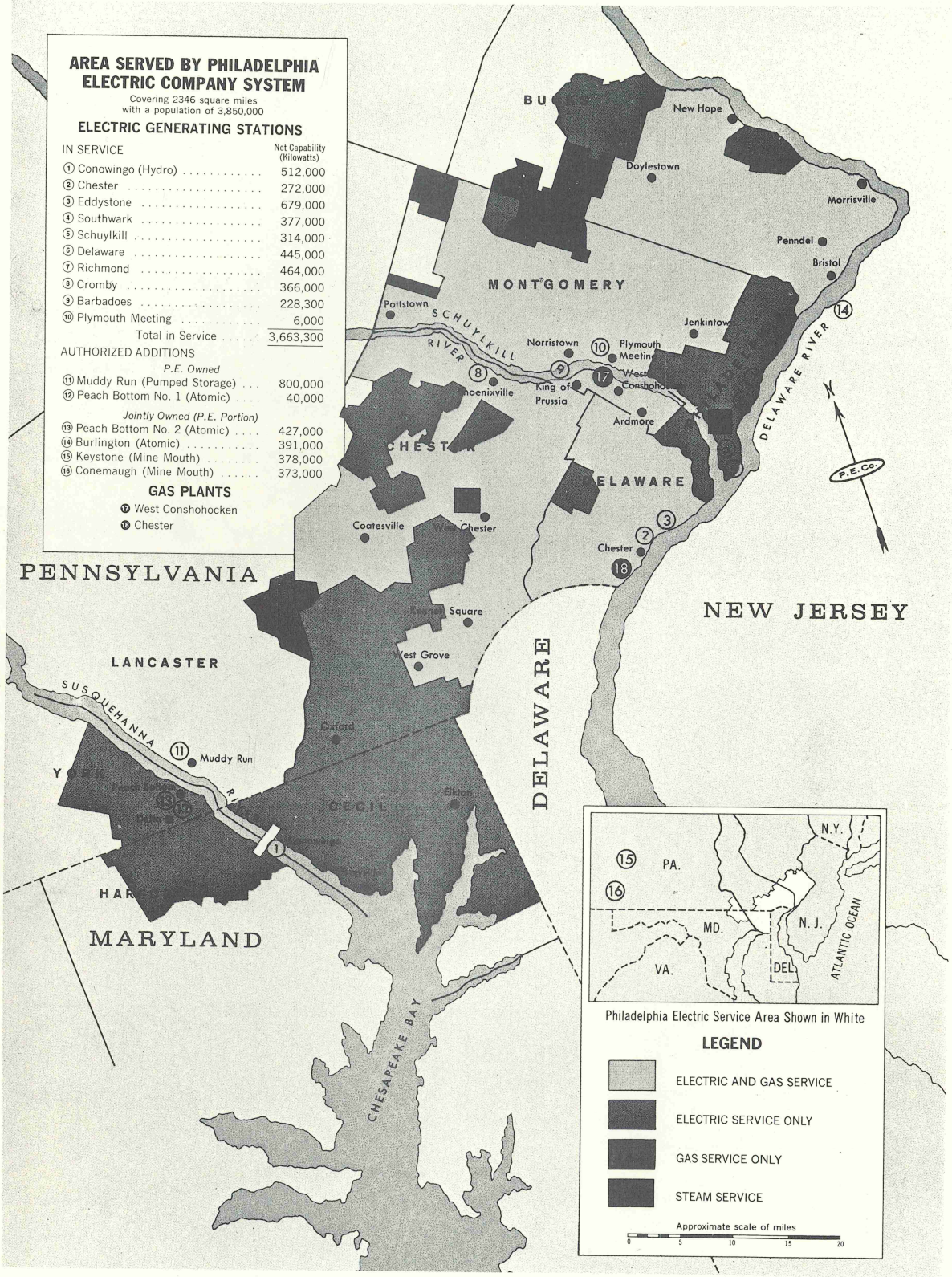


Figure IV - 1. Area Served by the Philadelphia Electric Company.

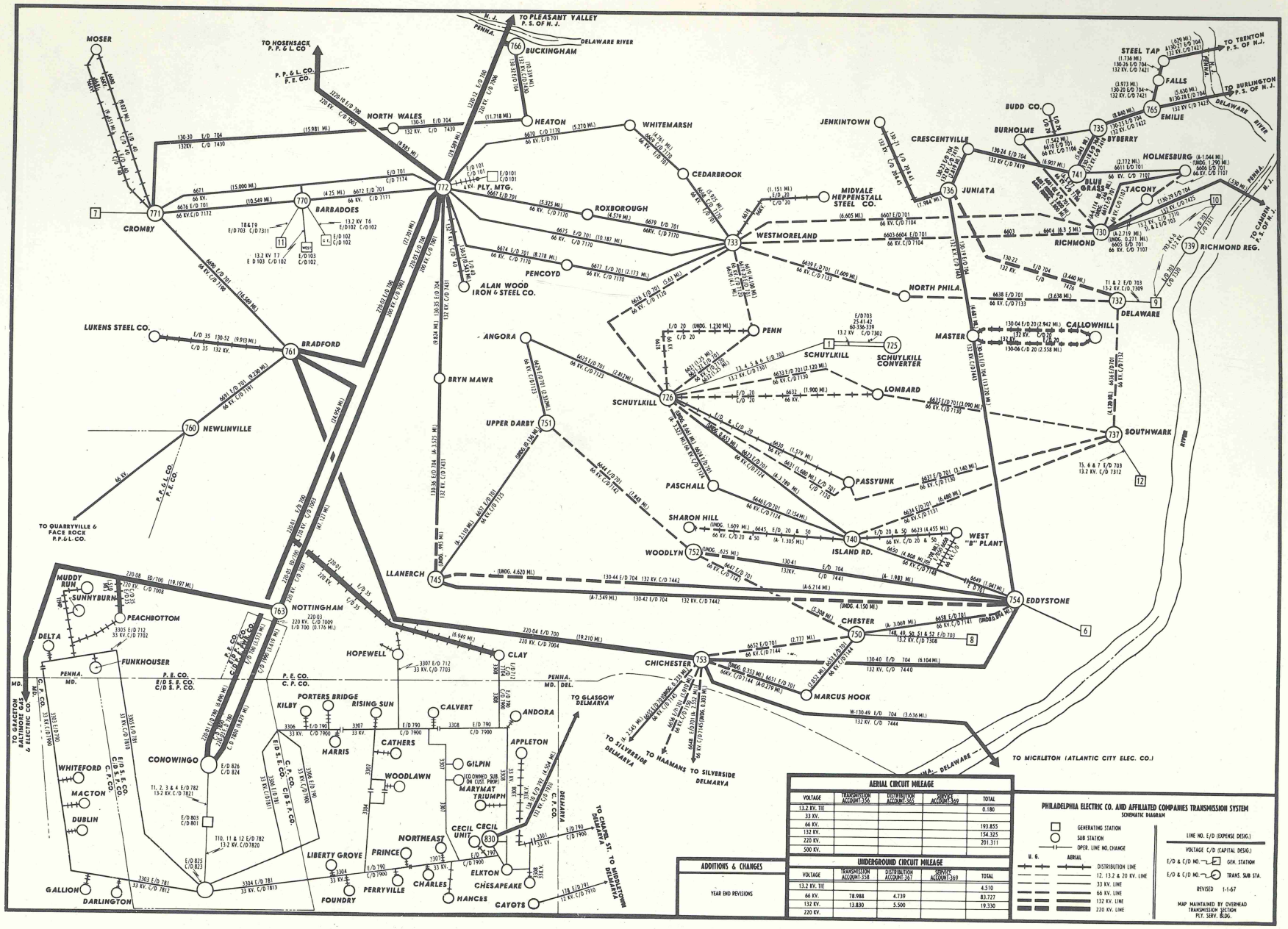


Figure IV - 2. Transmission System Schematic Map.

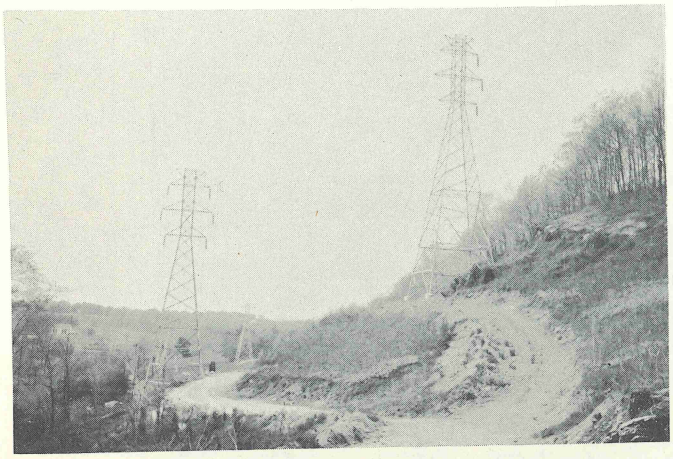


Figure IV-3. Typical 69KV Lattice Steel Tower Line Located on Hilly R/W.

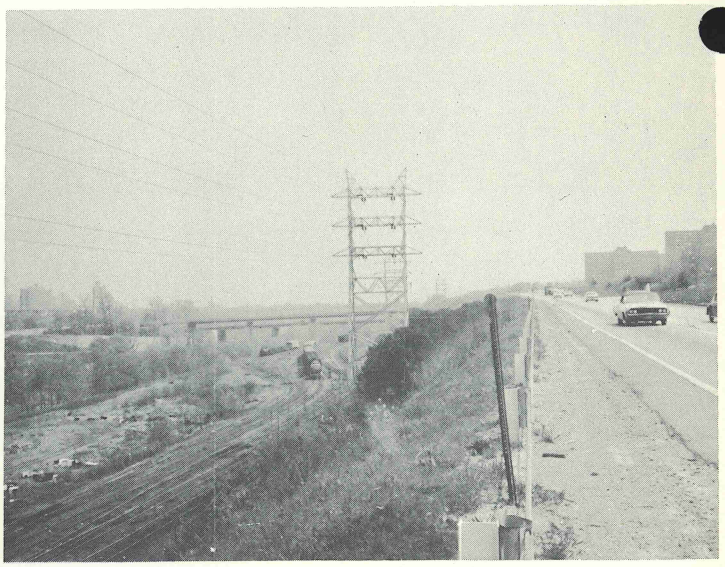


Figure IV-4. Four-Circuit 69KV Line Located on Bank Between a Railroad and an Expressway

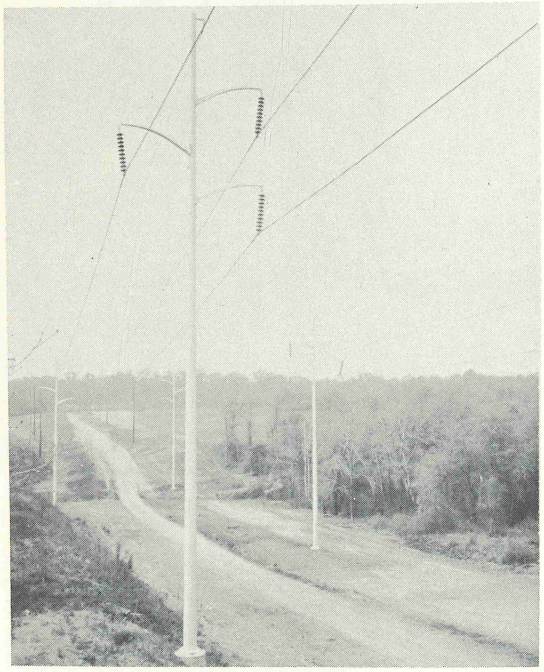


Figure IV-5. Typical 132KV Poly-12 Steel Pole

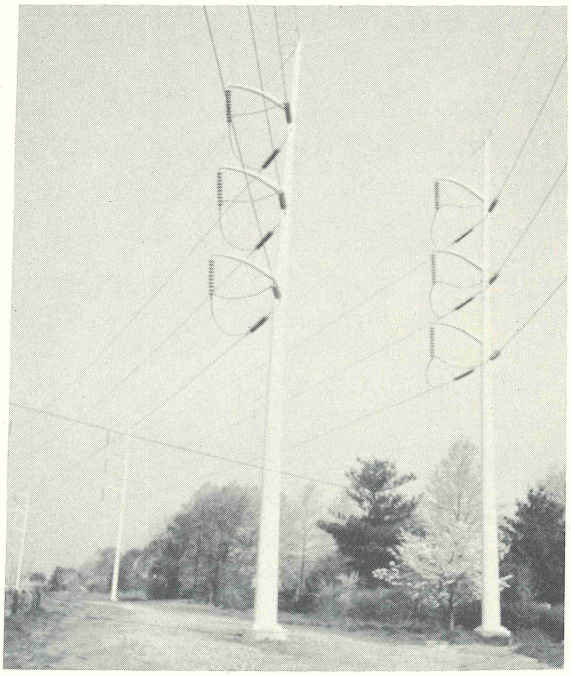


Figure IV-6. Poly-12 Steel Pole Dead-end Structure

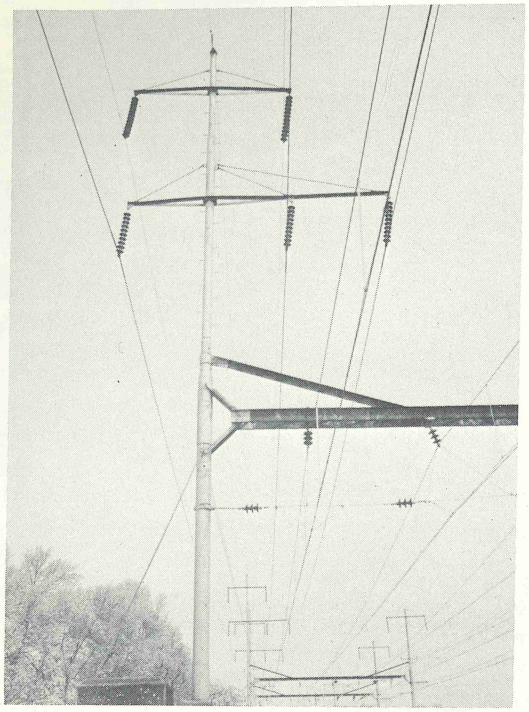


Figure IV-7. Example of 132KV Transmission Line Supported by Steel Pole. P. E. Co. Line is on Second Arm Supporting Three Conductors.

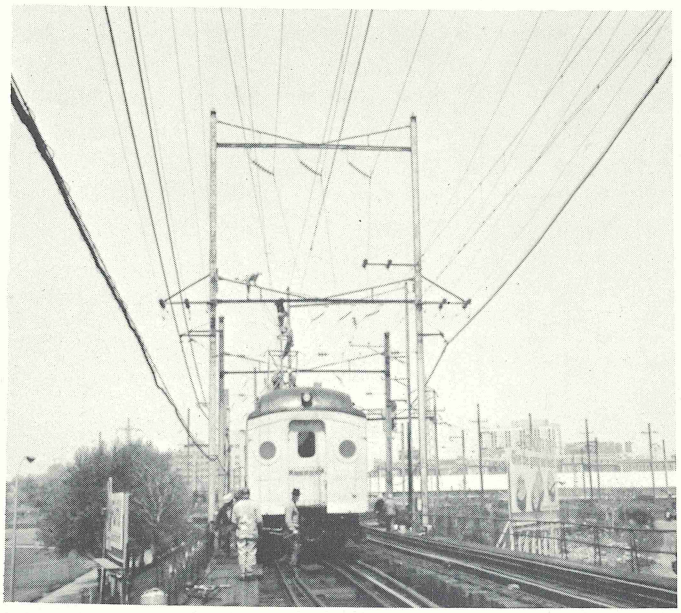


Figure IV-8. P. E. Co. 69KV Line Supported by Top Horizontal Beam. Line Located on Railroad Trestle and is Above Other Railroad Electrification.

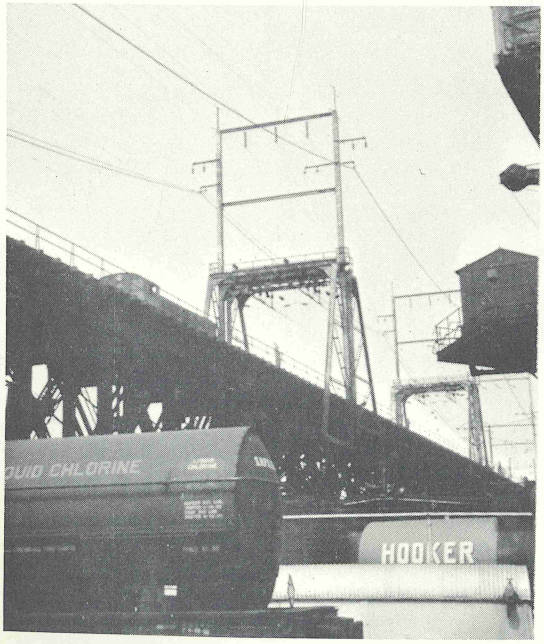


Figure IV-9. Transmission Line Supported by Steel Columns installed in Conjunction with Railroad Elevated Line. P. E. Co. Line Located at Top of Structure on Horizontal Beam.

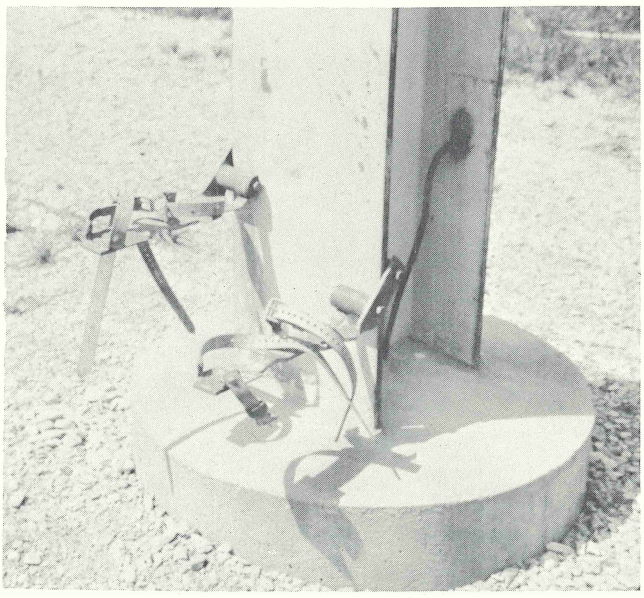


Figure IV-10. "Skates" used to Permit the Climbing of Steel Column-Type Structures.

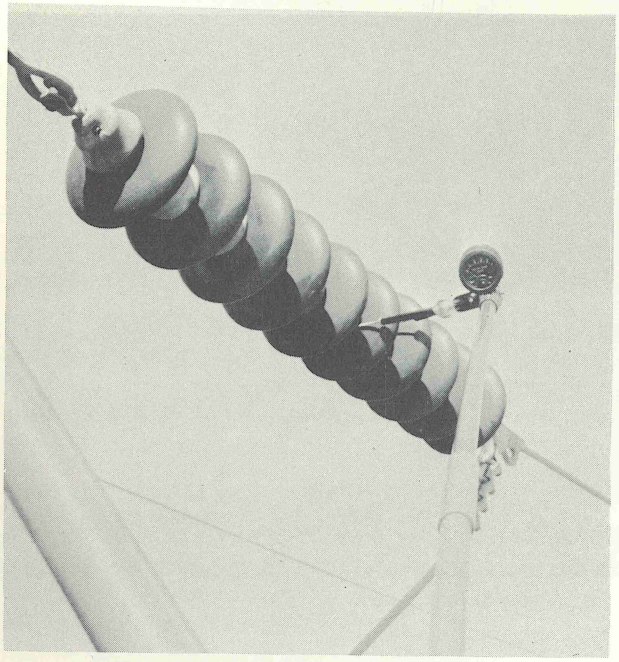


Figure IV-11. Checking Insulator Condition Using the Live Line Insulator Tester.

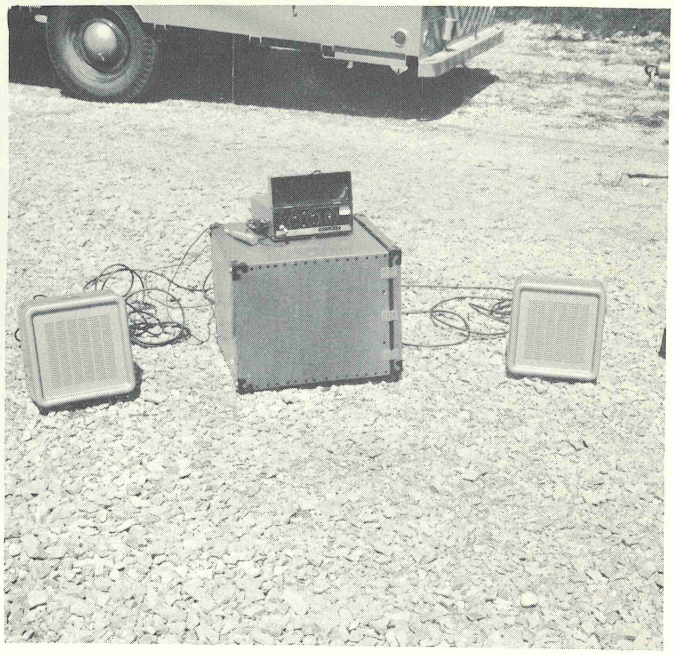


Figure IV-12. Portable Amplifier and Speakers Used by Crews for Ground to Tower Communications.

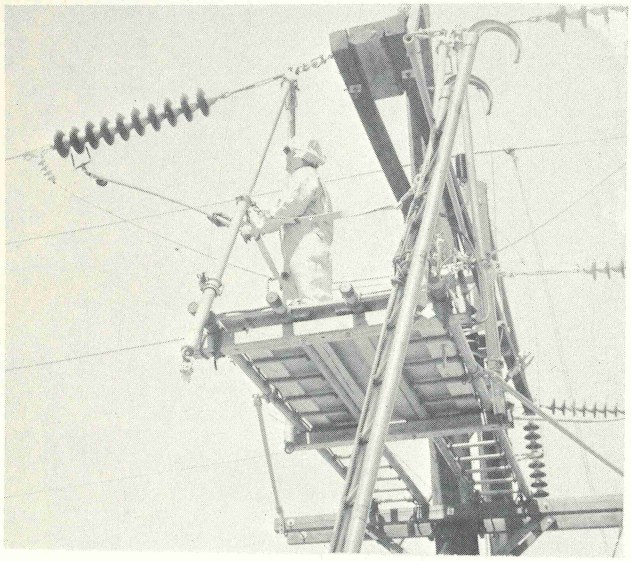


Figure IV-13. Lineman on Bare-hand Platform Wearing Conducting Suit Making a Test of Insulation Using the Live Line Insulator Tester.

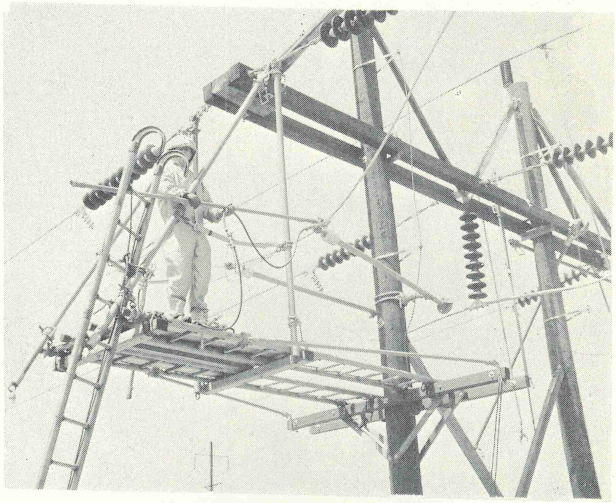


Figure IV-14. Lineman on Bare-hand Platform loading Platform to Energized Conductor.

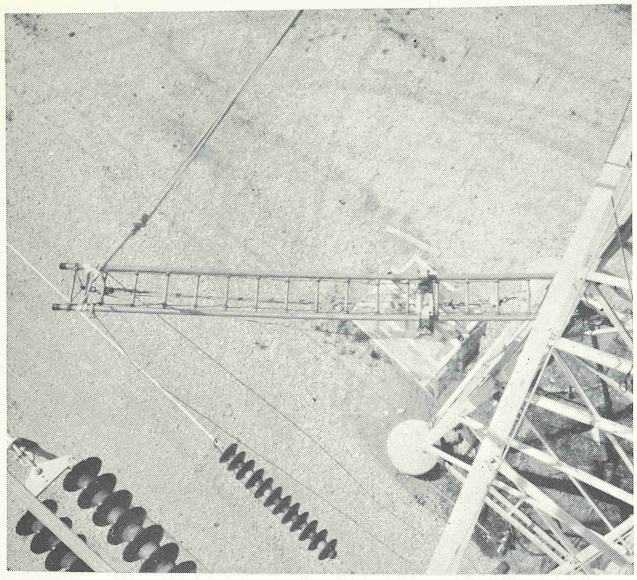


Figure IV-15. View from Line of Shielded Cart Supported by Epoxiglas Insulated Ladder.

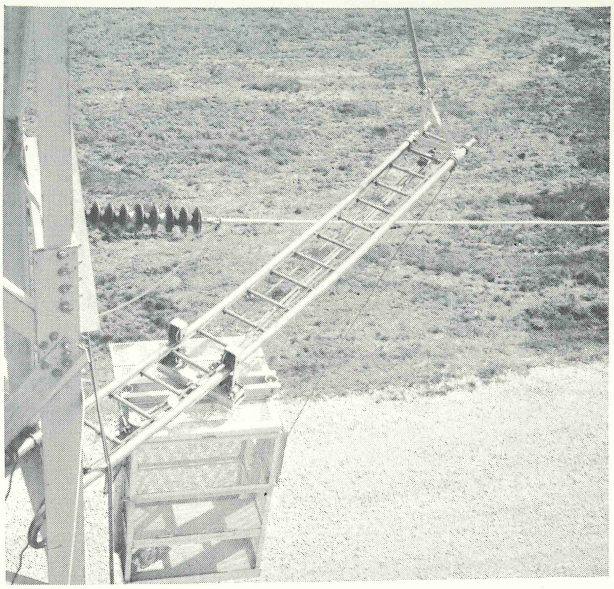


Figure IV-16. Shielded Cart Supported by Insulated Ladder Prior to Movement Out to Energized Conductor.

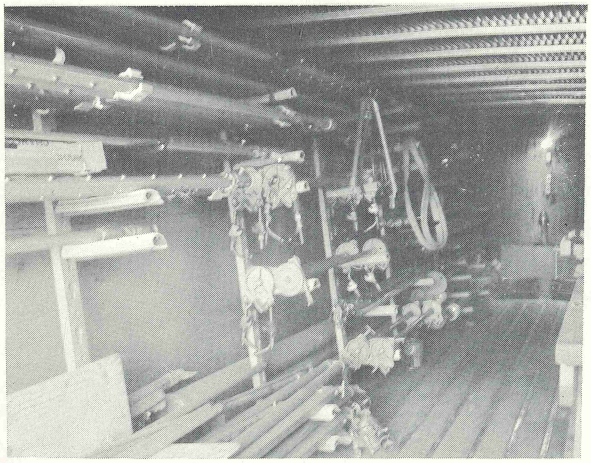


Figure IV-17. Interior of Van Trailer Used to Store and Transport Hot Sticks and Related Line Items.

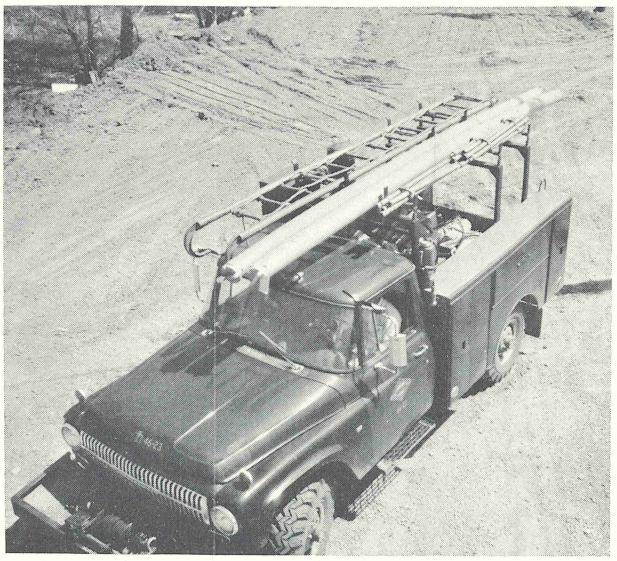


Figure IV-18. View of Pick-Up Truck Used to Tow Trailers and Transport Larger Length Sticks and Ladders.

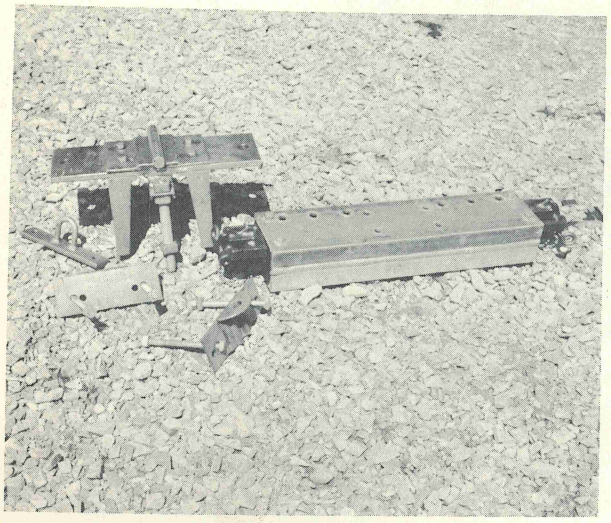


Figure IV 19. Pivot-Type Milking Stool Disassembled.

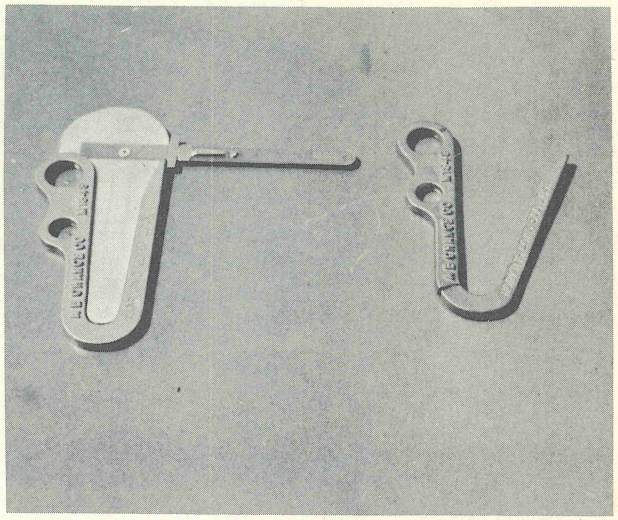


Figure IV-20. Metal Gauge Used to Permit Checking of Handline Hooks for Excessive Loading.

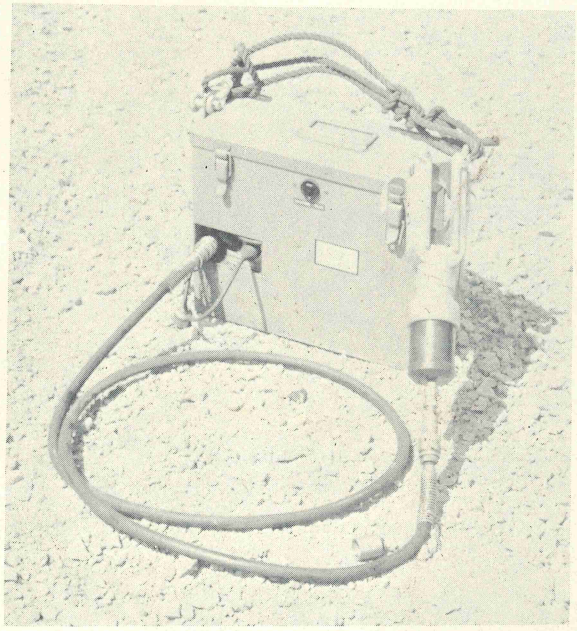


Figure IV-21. Battery Operated Hydraulic Cable Cutter

Charlie Q

MEMORANDUM

TO: All Supervisors

FROM: Paul Ankrim

SUBJECT: Roof Leaks Survey Report

DATE: May 3, 1989 (Wednesday)

==========

Attached are three different reports (six sheets of paper) relating to the factory leaks that were reported by Locke supervisors.

Each leak has a unique number and locator number. The number in most cases takes the Department Number and adds to it sequential two-digit numbers beginning with 01. Hence, for example, leak Number 02001 is the first leak reported by the Shipping Department.

Only the Ceramics Lab and High Voltage Lab have a different numbering system in this survey. (The specially prepared map for the Ceramics Lab is not attached to this report.)

The attached map records 68 of the 79 leaks' approximate positions. Those of the Ceramic Lab and High Voltage Lab are not plotted.

Please see the attached data recording form for understanding the various headings such as "Prior#1," "other-des," etc.

The reports are:

1. "Leaks Summary, All Fields--this provides an overview of all responses.

2. Three reports providing detailed information about leaks in each of the three classifications. The number of each classification is as follows:
    a. Dangerous: 24 (30.4 %), of which eight are in department 165 and four are in department 169.
    b. Hazardous: 21 (26.6 %), of which four are in department 161.
    c. Damaging: 34 (43.0%), of which half are equally shared by departments 020 and the ceramic lab.

Thank you very much for your cooperation in completing this survey. Perhaps you will discover leaks or condensation that are not recorded, especially from pipes, drain leaders, heaters, air conditioning tubes, etc. Please provide that information at your convenience.

Documenting the leaks was the easiest step; making the repairs is the real challenge, but you have my assurance that these will be made as efficiently and timely as possible.

LEAKS SUMMARY--ALL QUESTIONS
MAY 1, 1989

LEAK#	LOC#	PRIOR#1	PRIOR#2	TYPE	OTHER-DES	WEATH	DATE	TIME	NOTE	SURVEY-BY
16506	G21	DAMA	HEAVY	DIRECT		MED	890403	8:00 A.M.		MEL TAYLOR
16507	G22	DANG	HEAVY	DIRECT		MED	890403	8:00 A.M.		MEL TAYLOR
16508	N25	DANG	MEDIUM	DIRECT		MED	890403	8:00 A.M.		MEL TAYLOR
16509	N27	DANG	HEAVY	DIRECT		MED	890403	8:00 A.M.		MEL TAYLOR
16601	F17	HAZA	LIGHT	DIRECT		MED	890404	9:00AM		RED HARTLEY
16602	P5	HAZA	HEAVY	DIRECT		MED	890404	9:00AM		RED HARTLEY
16603	R6/7	HAZA	HEAVY	CONDEN		DRY	890405	8:00AM		RED HARTLEY
16701	KLMNO28	DAMA	HEAVY	DIRECT		HEV	890400	9:AM		EMMETT LEPLE
16702	O32	HAZA	HEAVY	DIRECT		HEV	890400	9:AM		EMMETT LEPLE
16703	O34	DAMA	HEAVY	DIRECT		HEV	890400	9:AM		EMMETT LEPLE
16704	H41	HAZA	HEAVY	DIRECT		HEV	890400	9:AM		EMMETT LEPLE
16705	O47	DAMA	HEAVY	DIRECT		HEV	890400	9:AM		EMMETT LEPLE
16901	B51	HAZA	MEDIUM	DIRECT		HEV				TOM NELSON
16902	D51	DAMA	HEAVY	SEWER		HEV				TOM NELSON
16903	D48	DANG	HEAVY	DIRECT		HEV				TOM NELSON
16904	SEE*	HAZA	HEAVY	DIRECT		HEV			* CHARGE FLOOR BETWEEN #7 AND #8	TOM NELSON
16905	H48	DANG	HEAVY	DIRECT		HEV				TOM NELSON
16906	F52	DANG	HEAVY	DIRECT		HEV				TOM NELSON
16907	B53	DANG	HEAVY	DIRECT		HEV				TOM NELSON
17001	D40	DAMA	MEDIUM	DIRECT		MED	890325	6:00 A.M.	Rain leader	JOHN GROSSKO
17002	B40	DAMA	MEDIUM	DIRECT		MED	890325	6:00 A.M.		JOHN GROSSKO
17003	B41	DAMA	MEDIUM	DIRECT		MED	890325	6:00 A.M.		JOHN GROSSKO
CLab01	AA70	HAZA	MEDIUM	DIRECT		MED				MILT VANIK
CLab02	BB70	DAMA	MEDIUM	DIRECT		MED				MILT VANIK
CLab03	BB73	DAMA	MEDIUM	DIRECT		MED				MILT VANIK
CLab04	BB76	DAMA	MEDIUM	DIRECT		MED				MILT VANIK
CLab05	CC74	DAMA	HEAVY	DIRECT		MED				MILT VANIK
CLab06	EE72	DAMA	LIGHT	DIRECT		MED				MILT VANIK
CLab07	FF72	DAMA	LIGHT	DIRECT		MED			Open hole in roof about 15" diameter	MILT VANIK
CLab08	FF73	DAMA	LIGHT	DIRECT		MED				MILT VANIK
CLab09	HH74	DAMA	LIGHT	DIRECT		MED				MILT VANIK
HVLab01	Note	HAZA	MEDIUM	INDI		MED			North end, where drain enters lab from roof	CHARLIE QUAM
HVLab02	Note	HAZA	MEDIUM	INDI		MED			Area between GCB assembly and high volt lab, in corner where die-bomb is located.	CHARLIE QUAM

Count: 79

LEAKS SUMMARY--ALL QUESTIONS
MAY 1, 1989

LEAK#	LOC#	PRIOR#1	PRIOR#2	TYPE	OTHER-DES	WEATH	DATE	TIME	NOTE	SURVEY-BY
02001	F07	DAMA	HEAVY	DIRECT		MED	890321	MORNING		DAN KALENDEK
02002	E08	DAMA	HEAVY	DIRECT		MED	890321	MORNING		DAN KALENDEK
02003	C11	DAMA	HEAVY	DIRECT		MED	890321	MORNING		DAN KALENDEK
02004	E12	DAMA	HEAVY	DIRECT		MED	890321	MORNING		DAN KALENDEK
02005	J7	DAMA	HEAVY	DIRECT		MED	890321	MORNING		DAN KALENDEK
02006	F23	HAZA	HEAVY	DIRECT		MED	890321	MORNING		DAN KALENDEK
02007	H23	DAMA	HEAVY	DIRECT		MED	890321	MORNING		DAN KALENDEK
02008	F27	DAMA	HEAVY	DIRECT		MED	890321	MORNING		DAN KALENDEK
02009	I25	DAMA	HEAVY	DIRECT		MED	890321	MORNING		DAN KALENDEK
02010	K25	HAZA	HEAVY	DIRECT		MED	890321	MORNING		DAN KALENDEK
15201	M38	DAMA	MEDIUM	CONDEN		HEV				JOHN WILLIAM
15202	G40	DANG	MEDIUM	DIRECT		MED/HEV				JOHN WILLIAM
15203	L/M46	DANG	HEAVY	DIRECT		MED/HEV				JOHN WILLIAM
15301	L31	DAMA	HEAVY	DIRECT	V-RAFTER; LEAKING A LONG WAY EVERY RAIN	ALL	890330	4:30 PM		JIM WILLHOIT
15302	L36	DANG	MEDIUM	DIRECT	POOR LIGHTING AND BAD FOOTING	HEV;MED	890406	7:00AM		JIM WILLHOIT
15303	H37	DANG	HEAVY;MEDIUM	DIRECT	LEAKS BETWEEN #5 & #6 DRYER; ELECTRICAL BOXES AND WARE AFFECTED	HEV;MED	890406	9:00AM		JIM WILLHOIT
15501	K05	DAMA	HEAVY	DIRECT		LITE	890415			CALVIN WILKI
15502	L10	DAMA	HEAVY	DIRECT		LITE	890415			CALVIN WILKI
15503	L11	DAMA	HEAVY	DIRECT		LITE	890415			CALVIN WILKI
15504	O09	DANG	HEAVY	DIRECT		LITE	890415			CALVIN WILKI
15505	O12	DANG	LIGHT	INDIR		LITE	890415			CALVIN WILKI
15506	Q11	DAMA	LIGHT	INDIR		LITE	890415			CALVIN WILKI
15507	O18	DAMA	HEAVY	INDIR		LITE	890415			CALVIN WILKI
15508	T12	HAZA	HEAVY	DIRECT		LITE	890415			CALVIN WILKI
15601	V22	DANG	HEAVY	DIRECT		MED/HEV			Leak 01 allows water to fall on electrical equipment.	Lee Hofmann
15602	S20	HAZA	HEAVY	INDIR		MED/HEV			Rain leader	Lee Hofmann
15603	Q22	HAZA	MEDIUM	INDIR		MED/HEV			Rain leader	Lee Hofmann
15604	S39	HAZA	HEAVY	INDIR		MED/HEV			Rain leader	Lee Hofmann
15605	T39	DAMA	MEDIUM	INDIR		MED/HEV			Broken skylight	Lee Hofmann
15606	K58	DANG	HEAVY	INDIR		MED/HEV			Rain leader and roof leak	Lee Hofmann
16101	L50	HAZA	MED	NO-INFO		MED/HEV				DAVID WALTHE
16102	J49	HAZA	HEAVY	NO-INFO		MED/HEV				DAVID WALTHE
16103	F57	HAZA	MEDIUM	NO-INFO		MED/HEV				DAVID WALTHE
16104	C55	HAZA	MEDIUM	NO-INFO		MED/HEV				DAVID WALTHE
16105	B54	DANG	HEAVY	NO-INFO		MED/HEV				DAVID WALTHE
16201	P40	DAMA	HEAVY	DIRECT		MED/HEV				MARK ROGERS
16202	V42	DANG	MED	SEWER					Drain in mold shop	MARK ROGERS
16203	H59	DAMA	HEAVY	DIRECT		MED/HEV				MARK ROGERS
16204	V42	DANG	MEDIUM	OTHER	BRICK WALL: WATER LEAKS THROUGH	HEV				MARK ROGERS
16401	T44	DANG	MEDIUM	DIRECT		MED	890321	9:30 AM		CURT FARRARE
16402	P45	HAZA	LIGHT	DIRECT		MED	890321	9:30 AM		CURT FARRARE
16501	027	DANG	MEDIUM	INDIR		MED	890403	8:00 A.M.		MEL TAYLOR
16502	I28	DANG	MEDIUM	DIRECT		MED	890403	8:00 A.M.		MEL TAYLOR
16503	F28	DANG	MEDIUM	DIRECT		MED	890403	8:00 A.M.		MEL TAYLOR
16504	M23	DANG	LIGHT	DIRECT		MED	890403	8:00 A.M.		MEL TAYLOR
16505	M23	DANG	HEAVY	DIRECT		MED	890403	8:00 A.M.		MEL TAYLOR

DANGEROUS LEAKS REPORTED
MAY 1, 1989

LEAK#	LOC#	PRIOR#1	PRIOR#2	TYPE	REC#
15202	G40	DANG	MEDIUM	DIRECT	031
15203	L/M46	DANG	HEAVY	DIRECT	032
15302	L36	DANG	MEDIUM	DIRECT	014
15303	H37	DANG	HEAVY;MEDIUM	DIRECT	015
15504	O09	DANG	HEAVY	DIRECT	041
15505	O12	DANG	LIGHT	INDIR	042
15601	V22	DANG	HEAVY	DIRECT	024
15606	K58	DANG	HEAVY	INDIR	029
16105	B54	DANG	HEAVY	NO-INFO	051
16202	V42	DANG	MED	SEWER	035
16204	V42	DANG	MEDIUM	OTHER	037
16401	T44	DANG	MEDIUM	DIRECT	011
16501	027	DANG	MEDIUM	INDIR	059
16502	I28	DANG	MEDIUM	DIRECT	060
16503	F28	DANG	MEDIUM	DIRECT	061
16504	M23	DANG	LIGHT	DIRECT	062
16505	M23	DANG	HEAVY	DIRECT	063
16507	G22	DANG	HEAVY	DIRECT	065
16508	N25	DANG	MEDIUM	DIRECT	066
16509	N27	DANG	HEAVY	DIRECT	067
16903	D48	DANG	HEAVY	DIRECT	054
16905	H48	DANG	HEAVY	DIRECT	056
16906	F52	DANG	HEAVY	DIRECT	057
16907	E53	DANG	HEAVY	DIRECT	058

Count: 24

HAZARDOUS LEAKS REPORTED
MAY 1, 1989

LEAK#	LOC#	PRIOR#1	PRIOR#2	TYPE	REC#
02006	F23	HAZA	HEAVY	DIRECT	006
02010	K25	HAZA	HEAVY	DIRECT	010
15508	T12	HAZA	HEAVY	DIRECT	046
15602	S20	HAZA	HEAVY	INDIR	025
15603	Q22	HAZA	MEDIUM	INDIR	026
15604	S39	HAZA	HEAVY	INDIR	027
16101	L50	HAZA	MED	NO-INFO	047
16102	J49	HAZA	HEAVY	NO-INFO	048
16103	F57	HAZA	MEDIUM	NO-INFO	049
16104	C55	HAZA	MEDIUM	NO-INFO	050
16402	P45	HAZA	LIGHT	DIRECT	012
16601	F17	HAZA	LIGHT	DIRECT	016
16602	P5	HAZA	HEAVY	DIRECT	017
16603	R6/7	HAZA	HEAVY	CONDEN	018
16702	O32	HAZA	HEAVY	DIRECT	020
16704	H41	HAZA	HEAVY	DIRECT	022
16901	B51	HAZA	MEDIUM	DIRECT	052
16904	SEE*	HAZA	HEAVY	DIRECT	055
CLab01	AA70	HAZA	MEDIUM	DIRECT	070
HVLab01	Note	HAZA	MEDIUM	INDI	068
HVLab02	Note	HAZA	MEDIUM	INDI	069

Count: 21

DAMAGING LEAKS REPORTED
MAY 1, 1989

LEAK#	LOC#	PRIOR#1	PRIOR#2	TYPE	REC#
02001	F07	DAMA	HEAVY	DIRECT	001
02002	E08	DAMA	HEAVY	DIRECT	002
02003	C11	DAMA	HEAVY	DIRECT	003
02004	E12	DAMA	HEAVY	DIRECT	004
02005	J7	DAMA	HEAVY	DIRECT	005
02007	H23	DAMA	HEAVY	DIRECT	007
02008	F27	DAMA	HEAVY	DIRECT	008
02009	I25	DAMA	HEAVY	DIRECT	009
15201	M38	DAMA	MEDIUM	CONDEN	030
15301	L31	DAMA	HEAVY	DIRECT	013
15501	K05	DAMA	HEAVY	DIRECT	038
15502	L10	DAMA	HEAVY	DIRECT	039
15503	L11	DAMA	HEAVY	DIRECT	040
15506	Q11	DAMA	LIGHT	INDIR	043
15507	O18	DAMA	HEAVY	INDIR	044
15605	T39	DAMA	MEDIUM	INDIR	028
16201	P40	DAMA	HEAVY	DIRECT	034
16203	H59	DAMA	HEAVY	DIRECT	036
16506	G21	DAMA	HEAVY	DIRECT	064
16701	KLMNO28	DAMA	HEAVY	DIRECT	019
16703	O34	DAMA	HEAVY	DIRECT	021
16705	O47	DAMA	HEAVY	DIRECT	023
16902	D51	DAMA	HEAVY	SEWER	053
17001	D40	DAMA	MEDIUM	DIRECT	033
17002	B40	DAMA	MEDIUM	DIRECT	080
17003	B41	DAMA	MEDIUM	DIRECT	081
CLab02	BB70	DAMA	MEDIUM	DIRECT	071
CLab03	BB73	DAMA	MEDIUM	DIRECT	072
CLab04	BB76	DAMA	MEDIUM	DIRECT	073
CLab05	CC74	DAMA	HEAVY	DIRECT	075
CLab06	EE72	DAMA	LIGHT	DIRECT	076
CLab07	FF72	DAMA	LIGHT	DIRECT	077
CLab08	FF73	DAMA	LIGHT	DIRECT	078
CLab09	HH74	DAMA	LIGHT	DIRECT	079

Count: 34

LEAKS: ROOF, PIPE, OTHER

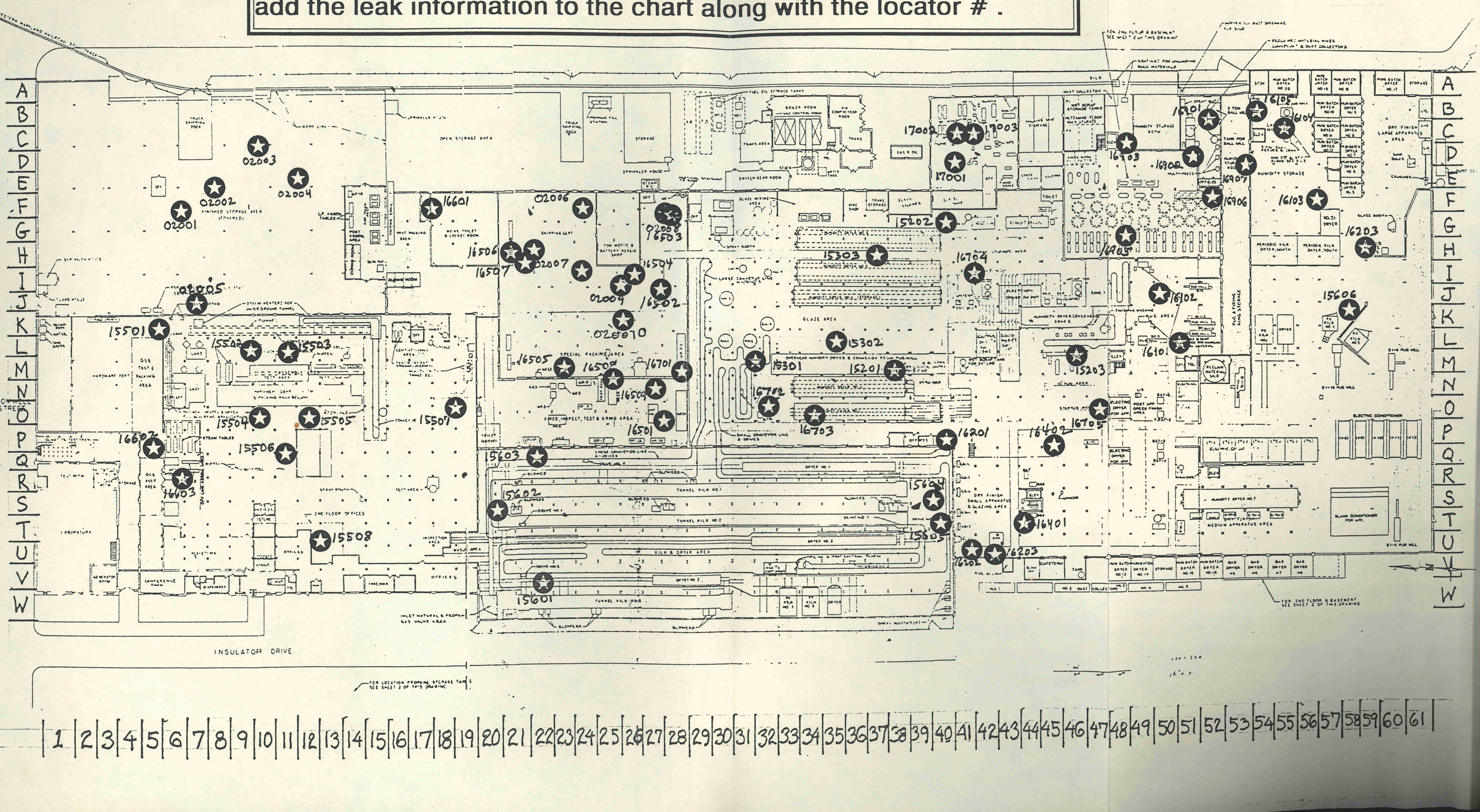
Locke Insulators, Inc., Baltimore, Maryland

LEAK NUMBER	LOCATOR CODE NUMBER	PRIORITY RATING							TYPE OF LEAK							SURVEY CONDITIONS				
		Dangerous	Hazardous	Damaging	Heavy Amount	Medium Amount	Light Amount	Trace Drops	Direct Drop	Indirect Source	Water Pipe	Sewer	Steam Pipe	Condensation	Other: Identify	OUTSIDE RAIN Hev	Med	Lite	WHEN ? Date	Tme

SPECIAL NOTES [Reference Leak #'s]:

LEAKS SURVEY

For each leak you identify, please draw a small red circle with an X inside and place a number near it, numbering from 01 to 99; then add the leak information to the chart along with the locator # .


A B C D E F G H I J K L M N O P Q R S T U V W
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61
CROMWELL STREET
INSULATOR DRIVE
02001
02002
02003
02004
02005
02006
02007
02008
02009
02010
15501
15502
15503
15504
15505
15506
15507
15508
15601
15602
15603
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16710
17001
17002
17003
15201
15202
15203
15301
15302
15303
16101
16102
16103
16201
16202
16203
16401
16402
16403
16901
16902
16903
16904
16905
16906
16907
BOILER ROOM
AIR COMPRESSOR ROOM
SWITCH GEAR ROOM
STORAGE
TRUCK SHIPPING DOCK
OPEN STORAGE AREA
SPRINKLER HOUSE
FUEL OIL STORAGE TANKS
TRUCK FUELING STATION
TRANS. AREA
SHIPPING DEPT.
SPRAY BOOTH
GLAZE MIXING AREA
PIPE SHOP
TRANS. STORAGE
TOILET
OFFICES
SILO
DUST COLLECTOR
RAW MATERIAL STORAGE
HUMIDITY STORAGE ROOM
MULTIPRESS
TAKE FOR BALL MILL
HUMIDITY STORAGE
HUB BATCH DRYER NO 20
HUB BATCH DRYER NO 19
HUB BATCH DRYER NO 18
HUB BATCH DRYER NO 17
STORAGE
DRY FINISH LARGE APPARATUS AREA
HUB BATCH DRYER NO 9
HUB BATCH DRYER NO 8
HUB BATCH DRYER NO 7
HUB BATCH DRYER NO 6
HUB BATCH DRYER NO 5
HUB BATCH DRYER NO 4
HUB BATCH DRYER NO 3
HUB BATCH DRYER NO 2
HUB BATCH DRYER NO 1
PERIODIC KILN DRYER NORTH
PERIODIC KILN DRYER SOUTH
NO. 21 DRYER
GLAZE BOOTH
PUG & STRING MINE STORAGE
PUG AREA
HUMIDITY DRYER (OVER-HEAD CONVEYOR TYPE)
OVERHEAD HUMIDITY DRYER & CONVEYOR PUG MILL
PUG MILL
DRY FINISH SMALL APPARATUS & GLAZING AREA
HUMIDITY DRYER NO. 7
MEDIUM APPARATUS AREA
ELECTRIC CONDITIONER
BLANK CONDITIONER FOR APP.
ELECTRIC DRYER FOR APP.
POST APP. GREEN FINISH AREA
CAFETERIA
TANK
NO. 1 DUST COLLECTOR
NO. 2 DUST COLLECTOR
NO. 3 DUST COLLECTOR
NO. 4 DUST COLLECTOR
NO. 5 DUST COLLECTOR
HUB BATCH DRYER NO. 13
HUB BATCH DRYER NO. 14
HUB BATCH DRYER NO. 15
HUB BATCH DRYER NO. 16
GAS DRYER #5
GAS DRYER #6
GAS DRYER #7
GAS DRYER #8
STORAGE
CALIBRATION
TUNNEL KILN NO. 1
TUNNEL KILN NO. 2
TUNNEL KILN NO. 3
KILN & DRYER AREA
DRYER NO. 1
DRYER NO. 2
DRYER NO. 3
DRYER NO. 4
DRYER NO. 5
DRYER NO. 6
DRYER NO. 7
KILN NO. 5
KILN NO. 6
KILN NO. 7
SMALL CONVEYOR LINE & DRIVES
LARGE CONVEYOR LINE A-DRIVES
LARGE CONVEYOR LINE B-DRIVES
GLAZE AREA
PUPOSE BUILT NO. 1
PUPOSE BUILT NO. 2
PUPOSE BUILT NO. 3
PUPOSE BUILT NO. 4
SPECIAL PACKING AREA
FIRED, INSPECT, TEST & GRIND AREA
INSPECTION AREA
TEST AREA
TEST PITS
SPRAY BOOTHS (4)
BLOWERS
DRIVE NO. 1
DRIVE NO. 2
DRIVE NO. 3
DRIVE NO. 4
DRIVE NO. 5
DRIVE NO. 6
DRIVE NO. 7
DRIVE NO. 8
DRIVE NO. 9
DRIVE NO. 10
DRIVE NO. 11
DRIVE NO. 12
DRIVE NO. 13
DRIVE NO.

Mechanics

BASIC CONCEPTS IN THE DESIGN OF ELECTRICAL BUS FOR SHORT CIRCUIT CONDITIONS

A. C. Bates

INTRODUCTION

The adequacy of the mechanical structure of an electrical bus to withstand short circuit forces has been an engineering consideration for many years. During this time the problem must have occupied the attention of many capable engineers, and as a result one would expect to find a basic knowledge of the subject widespread. However this does not seem to be true. Possibly this is because there may have been insufficient economic pressure to cause a deviation from an over simplified method which resulted, fortunately, in an over strong structure. Another possible reason is that the subject demands both electrical and mechanical analysis. Unfortunately, the electrical engineer tends to drop his careful thinking once the electrical considerations are analyzed, and the mechanical engineer may have trouble in making an adequate analysis because of insufficient knowledge of the electrical origin of the problem. Whatever the reason, confusion seems to exist, and the purpose of this paper is to make an earnest attempt to contribute information which will lead to an appreciation of the basic elements of the problem.

LIMITATION OF TREATMENT

There are many questions which might be asked about the design of a new bus structure for an intended service, or the analysis of the adequacy of an old one for a new service condition. The answers to such questions must result from an analysis, and hence must be deferred until at least some acceptably approximate analysis has been made.

It is necessary drastically to limit the subject matter in order to permit a grasp of the elementary aspects of the problem. For this purpose, a single phase circuit employing parallel conductors on rigid supports has been chosen.

THE CIRCUIT, CURRENT, AND FORCE

An ideal single phase circuit is shown in Fig. 1. The R and X are the total resistance and reactance involved in the current flow, and E is an ideal voltage source having no impedance. It is assumed that the switch is closed at the time necessary to produce the greatest initial offset of the current wave. With i representing the instantaneous value of current, and I_{sp} the peak value of symmetrical or steady state current, the offset wave may be expressed as:

$$\frac{i}{I_{sp}} = e^{-\frac{R}{X}\omega t} - \cos\omega t \quad . \qquad (1)$$

An oscillogram of the current wave would appear as shown by the full line in Fig. 2. If a limiting case of no decrement ($R/X = 0$) had been considered, the current wave instead of being as shown by the full line in Fig. 2 would have been wholly on one side of the zero line and tangent to it. The peaks of this wave, which have been shown dotted in Fig. 2, would have been of the same magnitude and would have continued indefinitely. This case of course is academic, since it is a limit which never exists.

Since force per unit length of conductor is proportional to current squared, the following expression is obtained from equation (1):

$$F = P\left(e^{-\frac{R}{X}\omega t} - \cos \omega t\right)^2 = P\left\{\tfrac{1}{2} + e^{-2\frac{R}{X}\omega t} - 2e^{-\frac{R}{X}\omega t}\cos \omega t + \tfrac{1}{2}\cos 2\omega t\right\}. \qquad (2)$$

Note: $\cos^2 \omega t = \tfrac{1}{2} + \tfrac{1}{2}\cos 2\omega t.$

If one could contrive to make an oscillogram of the force, it would appear as in Fig. 3. If no decrement had been assumed, the peaks would have been higher and recurrent as shown dotted in Fig. 3. The wave would have been wholly on one side of the axis and tangent to it.

A MATHEMATICAL SOLUTION

In order to have a familiar and widely used treatment of the problem as a comparison reference, a digression will be made here to describe that treatment which, as a matter of convenience in the remainder of the paper, will be referred to as the conventional method.

In the conventional method the consideration of electrical decrement is dispensed with by taking it as zero. The current and force oscillograms are of the recurrent high peak type as pointed out in the discussion of Figs. 2 and 3. This high peak value of instantaneous force is selected, and its effect on the structure is evaluated by means of the ordinary formulas of strength of materials. The significance of this statement is that the load is considered as statically applied, or that the structure possesses elasticity but no mass.

SIMPLIFICATION OF MECHANICAL SYSTEM

Returning to the previous discussion, Fig. 3 represents a force of appreciable complexity which is to be applied to a uniform conductor possessing distributed mass and distributed elasticity. Even though rigid supports are assumed, a precise solution is too involved for an initial attempt to grasp the elementary aspects of the problem. Therefore, an approximation is needed which will reduce the complexity to something easily handled, even though reality is knowingly sacrificed in some measure. The electrical engineer "lumps" his circuit constants to gain simplicity, and the mechanical engineer "concentrates" masses and elasticities. The same will be done here.

The conductor of Fig. 4a is intended to have distributed mass and elasticity. In Fig. 4b the conductor is considered elastic but massless, and a selected portion of the actual mass of the conductor has been concentrated in the middle of the span. The amount of the concentrated mass is that which will make the natural frequency of the structure shown in Fig. 4b the same as that of the original conductor shown in Fig. 4a when the conductor vibrates in the simple form of a single loop. There is no need to know just how much mass to concentrate. All that is necessary is to believe that there is an amount of mass which will make the frequencies the same.

Without any additional error or approximation, the conductor of Fig. 4b can be schematically represented as shown in Fig. 5. The dynamic response of the system of Fig. 5 to forces which are simple functions of time is treated in many undergraduate engineering text books. These books are good educational preparation but do not supply the solution here desired. In general, in the case under consideration, the driving force is different and the transient nature of the problem is emphasized, because only the maximum stress, deflection, or support loading is of major interest.

SOLUTION PRELIMINARIES

Although it is conceivable that a direct step-by-step process might be used to obtain a deflection solution corresponding to the force curve of Fig. 3, it is certainly easier and more clearly understandable to resolve the curve of Fig. 3 into the component parts shown in equation (2). These components are shown graphically in Fig. 6. The constant is curve 0. The exponential is curve 1. Particularly note that due to the operation of squaring the current to obtain force, the exponential in the force expression decays twice as rapidly as in the expression for current. To emphasize further, note that in the conventional method, the assumption of zero electrical decrement leads to zero decrement in the exponential force term, and hence this term reduces to an additional constant having a value of unity. Curve 2 shows the power frequency force term, and note that it decays at the same rate as the direct current component of the current wave of Fig. 2. If zero electrical decrement had been assumed, this force wave would have been ever present at the full initial amplitude as indicated by the dotted peaks of Fig. 6. Curve 3 represents a double frequency force term of constant amplitude. Note that, after the damped terms have diminished to unimportance, the continuously present remainder is $1/2 + 1/2 \cos 2\omega t$, which has a peak value of 1 but an average or static value of only 1/2. The electrical damping is responsible for the transition in character of the force wave of Fig. 3. The approach to reduced steady state conditions should be evident.

One further mental preparation may be necessary before presenting the solution for the case at hand. Consider the bus to be part of a resistive direct current circuit. The current would rise from an assumed negligible load value to short circuit value in zero time and then remain constant. The force would do likewise. The response of the bus bars would be an outward movement and an oscillation about a new position. The system of Fig. 5 would show the same type of response. The application of a stepped force to a spring without mass would produce a stepped graph of displacement and without oscillation. But the presence of the mass makes

the system capable of oscillation, and an oscillatory system cannot be disturbed without producing oscillation in some degree. If instead of applying the force suddenly, it had been applied as a force which increases to a final value and then remains constant, the amount of oscillation would become less for lower rates of build up of force. Time must be considered relative to the natural period of free vibration of the system. The oscillation serves the purpose of combining with the response associated with the force so as to permit the system to have the desired conditions of starting from zero displacement with zero velocity.

Now returning to the earlier discussion, the system of Fig. 5 is to be subjected to the component forces which appear in equation (2) and which have been discussed. The solution may be expected to contain terms which are quite similar to the force terms, and a free vibration term which will permit the proper starting conditions of zero displacement and velocity. For convenience, the solution will be said to consist of forced vibration terms and a free vibration term. It may be expected that all magnitudes will be functions of the relation of the constants of the system and the driving forces, with an important item being the ratio of the frequency of the driving force to the mechanical natural frequency of the system. Furthermore, because of the alternating character of two of the driving force terms, phase angles may be expected to enter the solution.

The solution will be quite similar to common cases treated in mechanical vibration, but different because of the electrical decrement assumed to be present in the electrical circuit. Because of the similarity and because of certain benefits, the solution will be presented in similar form.

THE SOLUTION

Using the system of Fig. 5 to represent the single phase bus on rigid supports, the solution for the deflection is:

$$4\frac{y}{y_{st}} = \tfrac{1}{2} + \frac{1}{Z_1} e^{-2\frac{R}{X}\omega t} - \frac{2}{Z_2} e^{-\frac{R}{X}\omega t}\cos(\omega t - \lambda_2)$$

$$+\frac{1}{2Z_3}\cos(2\omega t - \lambda_3) - ce^{-\frac{r}{\rho}\omega t}\cos\left(\frac{\sqrt{1-r^2}}{\rho}\omega t - \sigma\right). \qquad (3)$$

= constant + exponential term - power frequency term
+ double frequency term - free vibration term.

In order to gain an appreciation of the characteristics of the various terms in this equation, it is necessary to make some numerical calculations and plot some curves. As a particular example, the electric circuit R/X was chosen as 0.1, which corresponds to a circuit power factor of approximately 10%, and an amount of mechanical damping, represented by r, was taken as 0.05 times the value of critical damping (critical damping is explained in the Appendix). The values are thought to be in the range of the more usual applications. For these chosen values, curves are presented, in Figs. 7 and 8, for the various coefficients and phase angles as functions of the ratio of the frequency of the principal driving force, here the electrical power frequency, to the natural frequency of the

mechanical structure. It might have been preferable to use the reciprocal of this frequency ratio as abscissa since the driving force has a fixed frequency, and attention is directed to structures of different frequencies. However, if one will think in terms of period instead of frequency then the structure natural period increases toward the right. Irrespective of the mental viewpoint, an infinitely stiff structure is at the left of the plots and movement to the right corresponds to more flexible structures.

The various coefficients of the solution as functions of the frequency ratio, ρ, will now be discussed. The forced vibration coefficient due to the constant force is a constant having a value of 1/2, and is not shown in Fig. 7. The exponential coefficient starts at 1.0, and after an almost imperceptible rise it drops to lower values for more flexible structures, as shown by curve $1/Z_1$, Fig. 7. The power frequency coefficient increases in magnitude as the structure goes from an infinitely stiff structure to one that would be in resonance at the power frequency, and then drops as the structure is made still more flexible. See curve $2/Z_2$ of Fig. 7 for magnitude and λ_2 of Fig. 8 for the phase of the term relative to the force. This phase curve does not follow the usual curve of elementary mechanical vibration theory because of the inclusion of resistance in the electrical circuit. The double frequency coefficient is smaller than the power frequency coefficient, and it comes into resonance when the structure is reduced in flexibility only enough to cause its natural frequency to be the same as double the power frequency. The curve shape is very nearly the same as the previous curve, as shown by curve $1/(2Z_3)$ of Fig. 7. The phase corresponds to the usual mechanical vibration phase curve and is shown as λ_3 in Fig. 8. The magnitude of the necessary free vibration coefficient is shown by curve C, Fig. 7. The phase of this term is shown as σ in Fig. 8.

INVESTIGATION IN AN APPLICATION RANGE

These curves provide the raw material for proceeding with the study of a structure of any frequency one may wish to consider, but because of the many cases where the bus structure has a low natural frequency or a high period, further numerical consideration here has been on the right hand portion of Figs. 7 and 8, beyond the frequency ratio of 2. For 60 cycle electrical systems, buses have been considered having natural frequencies from a high of 30 cps down to a low of 2 cps.

For a specific case, the terms of the solution may be picked from curves and a vector diagram drawn, with the understanding that the result shall be obtained by projection of the vector sum on the vertical axis. A constant is a fixed vertical vector. The exponential is a vector which shrinks in magnitude but remains vertical. The power frequency vector rotates at power frequency and also shrinks. The double frequency vector rotates at double frequency but does not shrink. The free vibration vector shrinks and rotates corresponding to the constants of the mechanical system. For the cases here considered, the rotation of the free vibration vector is relatively slow compared to the power frequency vector.

Fig. 9 shows a vector diagram at the time, t = 0. If by command the vectors could start rotating and shrinking, all one would have to do would be to sit by and observe the maximum. Because of the relative size and phase of the free vibration term, the maximum will occur when that vector makes about a half turn. This is important because the more time it

takes for the free vibration vector to approach the vertical position, the greater has been the shrinkage that has taken place in the exponential and power frequency terms. Fig. 10 corresponds to Fig. 9 when time has progressed so that maximum conditions are obtained. The free vibration vector always shrinks by about the same percentage because it always makes about a half turn in order to create the first and largest maximum. Increase or decrease in mechanical damping increases or decreases the shrinkage of this vector. For a given structure, the ratio of the maximum here obtained to the maximum that would have been obtained from the conventional method is a convenient way to express the result. This form of expression permits comparison to a method that is familiar and simple.

RESULTS

The particular choice of $R/X = 0.1$ and $r = 0.05$ has been sufficient to permit a general discussion of the characteristics of the terms given in equation (3), and the manner in which a vector diagram yields a maximum value. However, when comparing the results of the analysis given in this paper with the results obtained by the conventional method, it is desirable to include results for additional choices of R/X and r. Having the maxima for a few combinations of system constants and a few frequencies will permit curves to be drawn which show the effect of the various constants on the response of the simplified system used here as a beginning approximation of the bus. Such curves are shown in Fig. 11. Note the use of a logarithmic abscissa scale for this figure.

These curves will now be discussed. Refer to Fig. 11. The conventional method corresponds to a straight horizontal line because the result is independent of the natural frequency of the structure. No forces due to mass were considered and the solution may be designated as static with $R/X = 0$. Introduce consideration of mass but retain zero electrical decrement and zero mechanical damping, and the upper curve is obtained. The result is a little higher than conventional on the left for the stiffest structure considered, and flattens out to a limit toward the right. The limit exists because certain terms neither decay nor change with the natural frequency of the structure.

For the next curve, zero electrical decrement is retained but considerable mechanical damping is introduced. The main effect is to permit the free vibration term to decrease with time, and the curve is lower and sweeps downward toward a limit. Since neither the introduction of the consideration of the dynamic forces nor the introduction of mechanical damping has indicated reduction in duty to the extent that some persons hope or believe possible, another combination of constants is used for the next curve. A reversion is made to zero mechanical damping and a reasonable electrical decrement is introduced. Now the exponential and power frequency vectors are permitted to shrink while the free vibration vector is rotating into position for the maximum. Also the exponential term is responsive to frequency and the curve sweeps low toward the right. Finally, with the addition of considerable mechanical damping a moderately lower curve is obtained.

Because of the results obtained here for structures having a ratio, ρ, equal to two or larger, one might conclude that the conventional method always gives safe results. This is distinctly not so. As the

structure is made stiffer, causing ρ to fall below two, a region of unsafe application of the conventional method is entered, and it is not until a very low value of ρ is reached (see Fig. 7) that the conventional method would again give acceptable results. Fortunately this unsafe region does not seem to correspond to structures as usually built.

DISCUSSION OF RESULTS

This analysis is elementary and somewhat oversimplified, but it does indicate that on new designs, savings may be made on conductor material, and on existing designs, the short circuit capacity may be markedly raised, if and only if the natural frequency is suitably low. The savings are permitted by:

1. Low natural frequency which causes the vibrational terms to be low,
2. Electrical damping which causes the exponential to be affected by natural frequency and causes the decay of both the exponential term and the power frequency term,
3. The combination of (1) with (2) so that enough time is available to allow the decaying terms to be reduced markedly.

The two principal factors which determine the ratio of the conductor deflection to the deflection calculated by the conventional method are the mechanical natural frequency and the R/X of the electrical circuit. Since the mechanical natural frequency, in effect, determines how many electrical cycles of current have passed before a maximum deflection is reached, it is indeed unclear how any method of averaging of peaks on a current oscillogram can be successful if it ignores consideration of the natural frequency of the structure, and if the resultant calculated force is used as a statically applied load.

LIMITATIONS

Why is the analysis given here not suitable for direct, unmodified application to bus design and analysis? Because the distributed mass and elasticity of the conductor make the problem more complicated. Several modes of vibration are possible. The conductor can vibrate in a simple shape with one loop. This is called the first mode and has the lowest natural frequency. It was for this mode of motion that Fig. 5 was drawn. However, there are higher modes possible with a number of loops corresponding to the number of the mode. For a bar with symmetrical conditions about its midpoint, only the odd modes 1, 3, 5, etc. are admissible. Modes are not harmonics. The frequencies are not in the ratio 1, 3, 5, etc. When the first mode has a low natural frequency relative to the power frequency, some one of the higher modes might be in resonance with either the power frequency force component or the double frequency force component. Fortunately, there are many factors which aid in holding down the influence of these resonant conditions on the maxima with which bus design is concerned. It is anticipated that an analysis which includes consideration of the higher modes might moderately raise the curves given here and give them a somewhat scalloped appearance due to the effects of resonance in the higher modes.

FURTHER WORK

Once the basic elements of the subject as herein set forth have been assimilated, consideration can be given to some of the remaining questions. Further development of the subject would start with one of the three following items and certainly eventually include all of them:

1. Consideration of a conductor with distributed mass and elasticity.
2. Consideration of a conductor on resilient supports which also possess mass.
3. Consideration of three phase conditions.

Although further work should be done, it is possible now to choose a "factor of remaining ignorance" and proceed to "package" the results in a form that requires only little knowledge to use. A set of curves for amperes, conductor spans, and conductor sizes would seem appropriate.

CLOSURE

This paper has been a sincere effort to promote the basic understanding of the problem by many of those persons who are concerned with the design or performance of electrical bus under short circuit conditions. The author's employment has nothing to do with this field and this paper would not have been written except for an unusual digression in a conversation with Mr. William Deans. Mr. Deans persuaded, and Messrs. G. E. Heberlein and J. B. Owens have by their interest made it easier to devote the necessary time.

It is hoped that the possibilities of economy, in which many people believe and which have been substantiated here, will lead to the development of a more rational basis for this important consideration in Engineering.

List of Captions

Fig. 1. The basic circuit.

Fig. 2. Current oscillogram, d.c. component shown as a dashed line. Calculated for R/X = 0.1, or power factor approximately 10%. Peaks for R/X = 0 are shown dotted.

Fig. 3. Force oscillogram. R/X = 0.1. Trends of major and minor peaks toward a steady state condition are shown by dashed lines. Peaks for R/X = 0 are shown dotted.

Fig. 4. The conductor and its elementary equivalent. (a) The conductor possessing distributed mass and elasticity. (b) The elementary equivalent. Conductor considered elastic but massless and a fraction of the mass placed at mid span.

Fig. 5. Schematic representation of Fig. 4(b). F = force, y = deflection, M = mass, K = spring constant, R' = damping coefficient. R' used to simulate the energy loss which always occurs in a vibrational structure.

Fig. 6. Component parts of the force shown in Fig. 3. These are the terms of equation (2) with P omitted. Curve 0, the constant term; curve 1, the exponential term; curve 2, the power frequency term; curve 3, the double frequency term. All full lines correspond to R/X = 0.1. Dotted peaks associated with curve 3 are for R/X = 0.

List of Captions - continued

Fig. 7. Coefficients of equation (3), calculated for R/X = 0.1, r = 0.05. The constant 1/2 is not shown. ρ = ratio of power frequency to mechanical natural frequency = ratio of natural period to power period. This paper considers only detailed numerical values for $\rho \geq 2.0$, but the curves are shown from $\rho = 0$. The curves in this lower range are necessary to full understanding and would be required if a more precise analysis were made. Curves for other low values of R/X and r are similar in character.

Fig. 8. The phase angles of the periodic terms of equation (3). λ_1, the phase angle of the power frequency term; λ_2, the phase angle of the double frequency term; σ, the phase angle of the free vibration term. Curves correspond to R/X = 0.1, r = 0.05. Curves for other low values of R/X and r are similar in character.

Fig. 9. Vector diagram of the terms of equation (3), for $\omega t = 0$. Drawn to scale for $\rho = 3$, R/X = 0.1, r = 0.05. Double frequency vector, occurring between the power frequency and free vibration vectors, is too small to show noticeably.

Fig. 10. The vectors of Fig. 9 at a later time when the first and major maximum occurs. Numerical data is the same as given for Fig. 9. Power frequency vector has made about 1-1/4 revolutions while the free vibration vector has made about 0.4 revolution.

List of Captions - continued

Fig. 11. Comparison of results in the range corresponding to high voltage bus conductors. The conventional method is used as reference. The pronounced effects of mechanical natural frequency and electrical decrement, R/X, are evident. The effect of mechanical damping is secondary.

Fig. 12. Vector diagram permitting the simplification of equation (8a) of the Appendix.

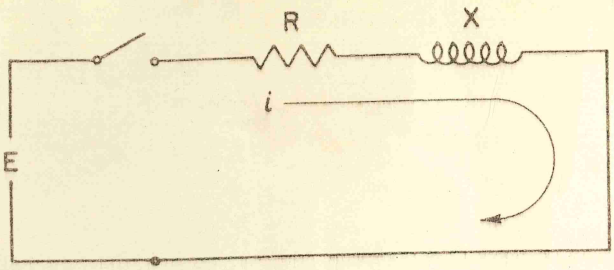

FIG. 1

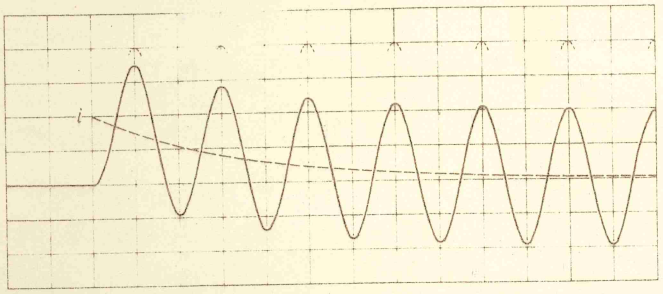

FIG. 2

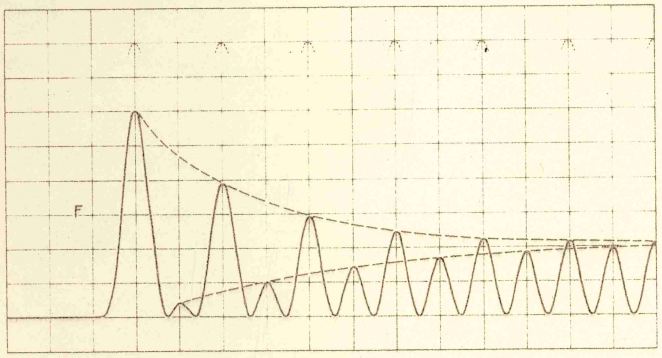

FIG. 3

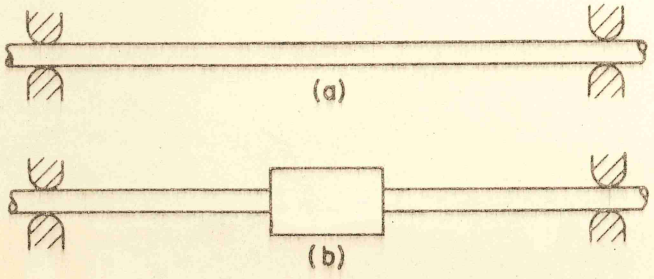

FIG. 4

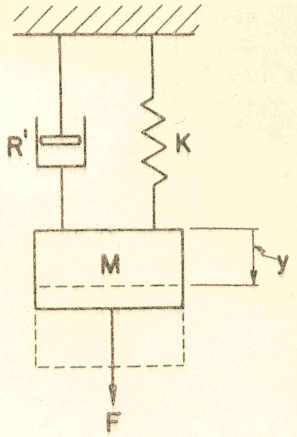

FIG. 5

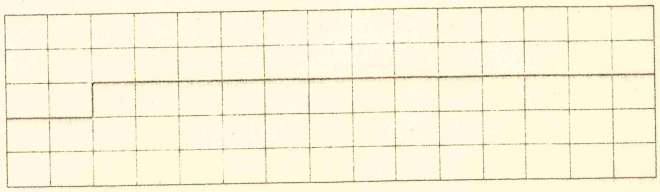

FIG. 6-0

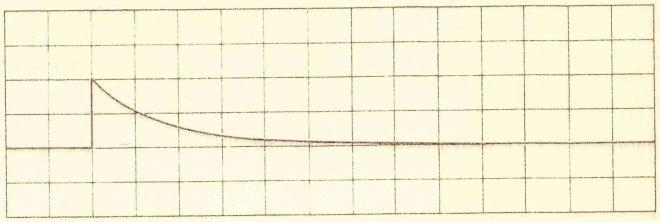

FIG. 6-1

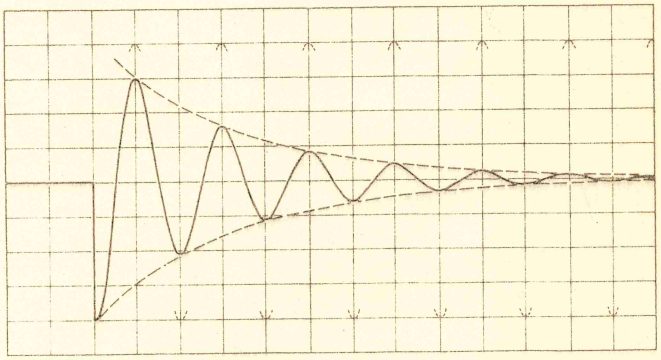

FIG. 6-2

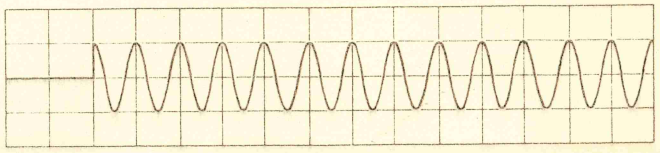

FIG. 6-3

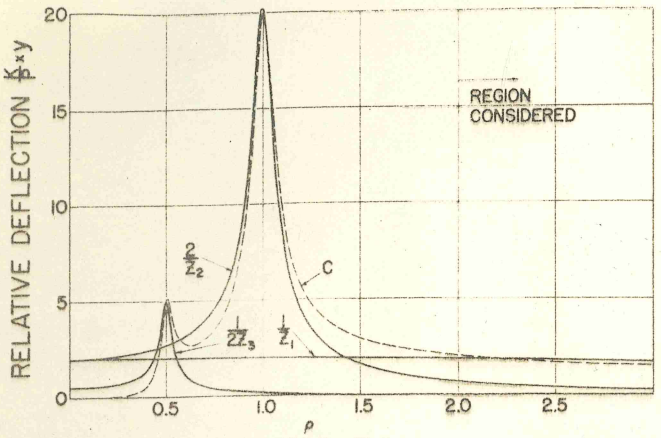

FIG. 7

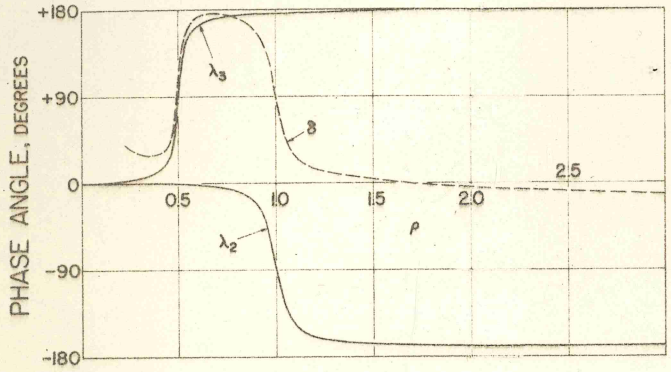

FIG. 8

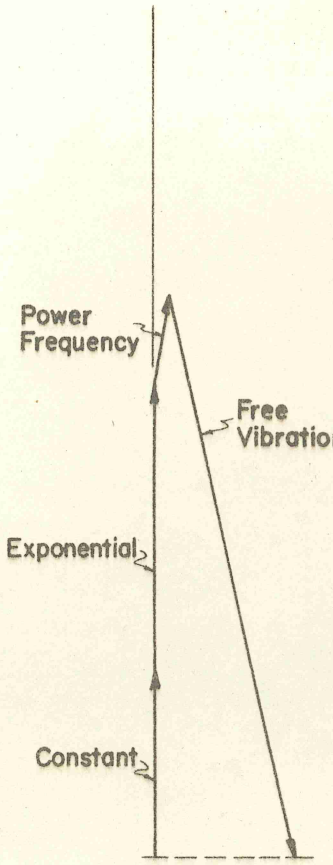

FIG. 9

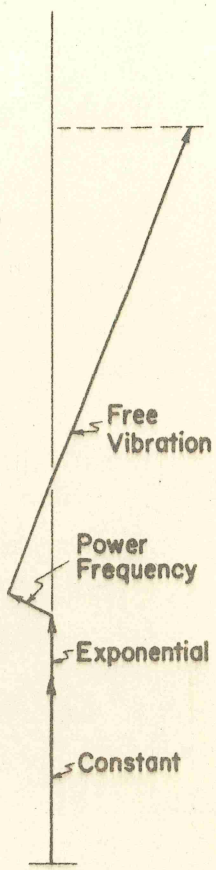

FIG. 10

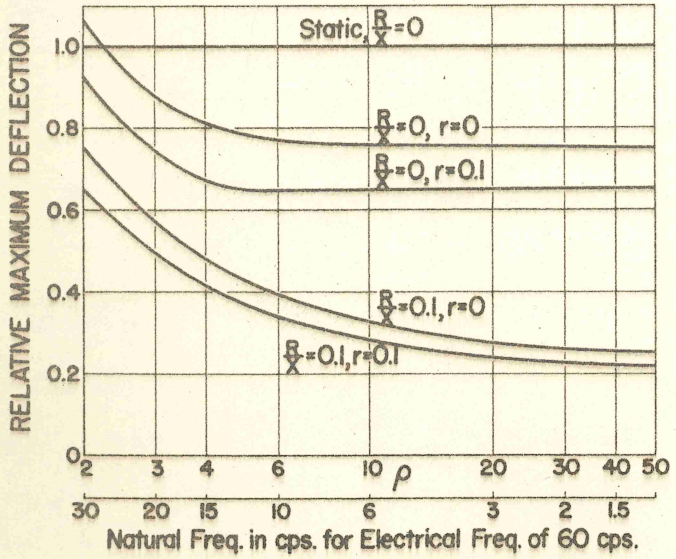

FIG. 11

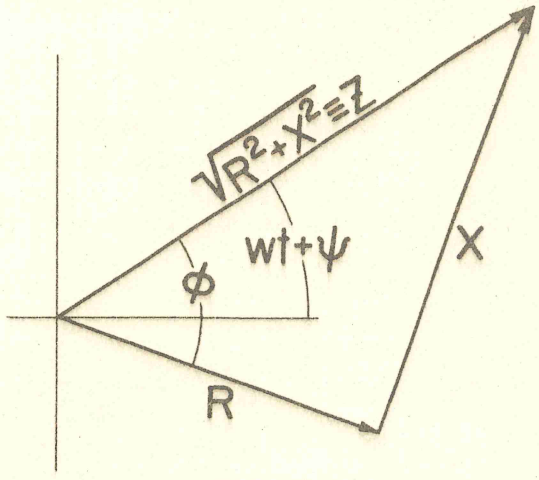

FIG. 12

APPENDIX

NOTATION

A = a constant, real or complex, to be evaluated.

a = magnitude of the real part of m.

B = a constant, real or complex, to be evaluated. Subscripts show association with m values.

b = magnitude of the imaginary part of m.

C = a positive magnitude of the free vibration of the mechanical system.

E = peak value of the sinusoidal voltage.

F = the electromagnetically developed force to be applied to the system of Fig. 5.

f = the electric power frequency.

f_o = frequency of free vibration of the system of Fig. 5, without damping.

I_{sp} = the magnitude of the symmetrical peak, or peak steady state short circuit current.

i = instantaneous value of short circuit current.

j = $\sqrt{-1}$ or a 90° operator.

K = spring constant, or force unit deflection.

L = inductance

M = equivalent mass of the bus conductor, or the mass shown in Fig. 5.

m = a complex number. Subscripts denote particular m's.

$\bar{m}$ = conjugate of m. Subscripts as in m.

n = a constant to be evaluated.

P = proportionality constant for force. For parallel bus bars at spacings great in comparison with the major cross sectional dimension of a bar, P may be given a value of 5.4×10^{-7}/s for a single phase or a d.c. circuit. This value of P used as a multiplier of the instantaneous current squared will give pounds of force per foot of conductor.

R = electrical resistance

R' = mechanical damping. Force per unit velocity.

r = ratio of mechanical damping considered to critical damping for the system of Fig. 5.

s = bus bar spacing in inches.

t = time

t_1 = time associated with maximum instantaneous current.

$X = \omega L$ = inductive reactance.

y = deflection of spring or mass in system of Fig. 5.

Y_{st} = the maximum deflection of the system of Fig. 5 obtained by the static application of the maximum force considering no electrical decrement. This is the deflection value obtained by the conventional method.

Z = impedance in an electrical equation.

NOTATION

= magnitude of a complex number $Z \angle \lambda$ when appearing in a mechanical system equation. Subscripts associate Z's and m's.

α = real component of the m associated with free vibration of the mechanical system.

β = imaginary component of the m associated with free vibration of the mechanical system.

$\delta = \pi/2 - \phi$ = deviation from a 90° relationship between steady state current and voltage.

λ = the angle of the complex number $Z \angle \lambda$ or $Ze^{j\lambda}$ Subscripts to associate λ, Z, and m.

$\rho = f/f_o$ or τ_o/τ, relative frequency or period.

σ = phase angle of free vibration.

$\tau = 1/f$ = period of electric power.

$\tau_o = 1/f_o$ = period of undamped free vibration of system of Fig. 5.

ϕ = phase angle, the angle of lag of current behind voltage.

ψ = a phase angle introduced in the voltage expression to facilitate investigation of the current resulting from different times of switch closure.

$\omega = 2\pi f$ = angular velocity of electric power current or voltage.

$\omega_o = 2\pi f_o$ = angular velocity of undamped free vibration of the mechanical system.

UNITS

In general it is not necessary to specify a system of units since answers are given in relative form. However practical volts, amperes, and ohms are intended for electrical quantities and pounds force, inches, and seconds, are intended for the other quantities.

ELECTRICAL

In order to permit the closing of the switch in Fig. 1 at any point in the voltage wave a phase angle, ψ, is incorporated in the expression for the voltage. ψ is to be assigned any desired value, or is to be determined for a desired condition. The differential equation for the circuit of Fig. 1 may then be written in the form:

$$L\frac{di}{dt} + Ri = E\sin(\omega t + \psi), \tag{4}$$

or employing $X = \omega L$ and using ωt instead of t as the independent variable equation (4) becomes:

$$X\frac{di}{d(\omega t)} + Ri = E\sin(\omega t + \psi). \tag{4a}$$

From either the physical knowledge of the problem including the fact that there usually is a direct current transient, or a knowledge of the mathematics of the equation, it is reasonable to assume a trial solution in the form:

$$i = Ae^{-n\omega t} + B\sin(\omega t + \psi - \varphi) \tag{5}$$

This will be the correct solution if values of A, B, and n may be determined such that the left member of equation (4a) reduces to the right member and the desired condition of zero current at zero time exists.

The two terms of the left member are obtained from operations on equation (5). The result is as follows:

$$X\frac{di}{d(\omega t)} = -AnXe^{-n\omega t} + BX\cos(\omega t + \psi - \varphi). \tag{6a}$$

$$Ri = ARe^{-n\omega t} + BR\sin(\omega t + \psi - \varphi). \tag{6b}$$

Since there is no exponential in the right member it is necessary that:

$$Ae^{-n\omega t}(R - nX) = 0, \tag{7a}$$

or
$$n = \frac{R}{X}. \tag{7b}$$

Equality of sinusoidal terms is necessary. Therefore:

$$B\left\{X\cos(\omega t + \psi - \varphi) + R\sin(\omega t + \psi - \varphi)\right\} = E\sin(\omega t + \psi). \tag{8a}$$

The vector diagram of Fig. 12 permits easy simplification of the brace in equation (8a). Equation (8a) is reduced to:

$$B\sqrt{R^2 + X^2}\sin(\omega t + \psi) = E\sin(\omega t + \psi), \tag{8b}$$

or
$$B = \frac{E}{\sqrt{R^2 + X^2}} = \frac{E}{Z}, \tag{8c}$$

and also from Fig. 12:

$$\tan \varphi = \frac{X}{R} \qquad (8d)$$

The necessary value of A has not been found, but neither has the initial condition of i = o at ωt = o been considered. Equation (5) for this condition becomes:

$$i = A + B \sin(\psi - \varphi) = 0 \quad . \qquad (9a)$$

B is given in (8c), hence:

$$A = -B \sin(\psi - \varphi) = -\frac{E}{Z} \sin(\psi - \varphi) . \qquad (9b)$$

Therefore the form of equation (5) which satisfies all requirements, and hence is the solution is:

$$i = \frac{E}{Z}\left\{ \sin(\omega t + \psi - \varphi) - e^{-\frac{R}{X}\omega t} \sin(\psi - \varphi) \right\} \quad . \qquad (10a)$$

Since in equation (4), E is the peak voltage,

$$\frac{E}{Z} = \text{peak symmetrical or steady current} \equiv I_{sp} . \qquad (10b)$$

Suppose that for a given circuit (R and X fixed) several values of ψ were chosen and enough values of i were calculated to determine the current at the major peak for each choice of ψ . Then by plotting these peak values versus ψ , the value of ψ for the highest obtainable peak could be found. For the value of ψ desired, the plot would have a horizontal tangent, or $di/d\psi = 0$. The same result may be obtained mathematically. The current will have a peak value at some time t_1 when the brace in equation (10a) is a maximum and therefore has a zero derivative with respect to ωt. This gives:

$$\cos(\omega t_1 + \psi - \varphi) + \frac{R}{X} e^{-\frac{R}{X}\omega t_1} \sin(\psi - \varphi) = 0 \qquad (11a)$$

or

$$e^{-\frac{R}{X}\omega t} \sin(\psi - \varphi) = -\frac{X}{R} \cos(\omega t_1 + \psi - \varphi) \qquad (11b)$$

Likewise differentiating the brace in equation (10a) with respect to ψ and requiring the result to be zero, the following equation is obtained:

$$\cos(\omega t_1 + \psi - \varphi) - e^{-\frac{R}{X}\omega t_1} \cos(\psi - \varphi) = 0 \ , \qquad (12a)$$

or

$$e^{-\frac{R}{X}\omega t_1} \cos(\psi - \varphi) = \cos(\omega t_1 + \psi - \varphi) . \qquad (12b)$$

Dividing equation (11b) by equation (12b) and noting equation (8d), there results:

$$\tan(\psi - \varphi) = -\frac{X}{R} = -\tan\varphi = \tan(-\varphi) . \qquad (13)$$

Hence $\psi = 0$ for the highest obtainable major peak, that is, the switch should be closed at a voltage zero. For this condition equation (10a) becomes:

$$i = \frac{E}{Z}\left\{\sin(\omega t - \varphi) + e^{-\frac{R}{X}\omega t}\sin\varphi\right\} \qquad (14)$$

For the case of most frequent interest φ will be near 90° or $\frac{\pi}{2}$, hence let:

$$\varphi = \frac{\pi}{2} - \delta \qquad (15)$$

Then:

$$\sin(\omega t - \varphi) = \sin(\omega t + \delta - \tfrac{\pi}{2}) = -\cos(\omega t + \delta), \qquad (16a)$$

and

$$\sin\varphi = \sin(\tfrac{\pi}{2} - \delta) = \cos\delta \qquad (16b)$$

Using these expressions equation (14) becomes:

$$i = \frac{E}{Z}\left\{e^{-\frac{R}{X}\omega t}\cos\delta - \cos(\omega t + \delta)\right\} \qquad (17)$$

If instead of taking $\psi = 0$ for maximum peak, ψ is taken as $-\delta$, then from equation (15),

$$\psi - \varphi = -\delta - \tfrac{\pi}{2} + \delta = -\tfrac{\pi}{2} \qquad (18)$$

Using equation (18) in equation (10a), there results:

$$i = \frac{E}{Z}\left\{\sin(\omega t - \tfrac{\pi}{2}) - e^{-\frac{R}{X}\omega t}\sin(-\tfrac{\pi}{2})\right\}, \qquad (19a)$$

or

$$i = \frac{E}{Z}\left\{e^{-\frac{R}{X}\omega t} - \cos\omega t\right\} \qquad (19b)$$

This may be written in non-dimensional form by use of equation (10b):

$$\frac{i}{I_{sp}} = e^{-\frac{R}{X}\omega t} - \cos\omega t \qquad (1)$$

This expression is simpler than equation (17) and has the highest value of direct current component, so may be said to have the maximum initial offset. For circuits of 10% power factor and less the major peak will be within less than 0.25% of the greatest obtainable major peak. For these reasons equation (1) was chosen as the basis of the initial work given in this paper.

With the complete analysis given in this paper, it would be just a matter of labor to convert to equation (17) as a base. However there is no apriori proof that equation (17) would yield worst conditions. The peak bus deflection is not simultaneous with the peak force.

MECHANICAL

The force arising from the electric current is given in the body of the paper as:

$$F = P\left\{\tfrac{1}{2} + e^{-2\frac{R}{L}\omega t} - 2e^{-\frac{R}{L}\omega t}\cos\omega t + \tfrac{1}{2}\cos 2\omega t\right\} . \qquad (2)$$

From a free body diagram, drawn for the convention adopted for positive displacement and positive force as shown in Fig. 5, the following differential equation is easily obtained:

$$M\frac{d^2y}{dt^2} + R'\frac{dy}{dt} + Ky = F . \qquad (20)$$

Suppose momentarily that F is taken as zero instead of being given by equation (2). Then equation (20) is changed to:

$$M\frac{d^2y}{dt^2} + R'\frac{dy}{dt} + Ky = 0 \qquad (21)$$

This is the equation of the mechanical system free of any driving force, and is one of the equations examined in elementary vibration theory. Usually the mass is considered displaced from its position of rest and released at time, t = 0. The return to zero displacement for different amounts of damping is investigated. When R' = 0 the system is oscillatory and the following relation exists:

$$\omega_o^2 = \frac{K}{M} = (2\pi f_o)^2 . \qquad (22)$$

When R' ≠ 0 the return of the mass from a displaced position will be oscillatory $R'/2M < \omega_o$, and aperiodic if $R'/2M > \omega_o$. If R' increases from a small value to a value where $R'/2M = \omega_o$, the oscillatory character becomes more damped and the frequency becomes lower until it reaches zero and the oscillations vanish. This amount of damping which corresponds to the boundary between oscillatory and aperiodic behavior is called critical damping. When damping is expressed as a fraction of critical damping the inference to the system behavior is immediate. Damping may be expressed in this way by r, where:

$$r = \left(\frac{R'}{2M}\right)/\omega_o . \qquad (23)$$

When r = 1.0 critical damping exists and the system is in the condition where a slight change in damping causes the behavior to become either oscillatory or aperiodic.

Relations (22) and (23) will be useful in rewriting equation (20) for the purpose of simplifying and clarifying the ensuing solution. It will be convenient to use ωt instead of t as the independent variable, therefore observe that:

$$\frac{d}{dt} = \omega\frac{d}{d(\omega t)} \qquad (24)$$

The application of this relation to equation (20) gives:

$$M\omega^2 \frac{d^2y}{d(\omega t)^2} + R'\omega \frac{dy}{d(\omega t)} + Ky = F \,. \qquad (25a)$$

Division of equation (25a) by $\omega_o^2 M$ gives:

$$\left(\frac{\omega}{\omega_o}\right)^2 \frac{d^2y}{d(\omega t)^2} + 2\frac{R'}{2M\omega_o} \times \frac{\omega}{\omega_o}\frac{dy}{d(\omega t)} + \frac{K}{\omega_o^2 M} y = \frac{K}{\omega_o^2 M} \times \frac{F}{K} \,. \qquad (25b)$$

Introduction of $\rho \equiv \omega/\omega_o$ and the use of relations (22) and (23) permit equation (25b) to be written in the form:

$$\rho^2 \frac{d^2y}{d(\omega t)^2} + 2r\rho \frac{dy}{d(\omega t)} + y = \frac{F}{K} \,. \qquad (25c)$$

With F as given by equation (2), equation (25c) becomes:

$$\rho^2 \frac{d^2y}{d(\omega t)^2} + 2r\rho \frac{dy}{d(\omega t)} + y = \frac{P}{K}\left\{\tfrac{1}{2} + e^{-2\beta\omega t} - 2e^{-\beta\omega t}\cos\omega t + \tfrac{1}{2}\cos 2\omega t\right\} \qquad (26a)$$

For F taken as zero, equation (26a) reduces to:

$$\rho^2 \frac{d^2y}{d(\omega t)^2} + 2r\rho \frac{dy}{d(\omega t)} + y = 0 \,. \qquad (26b)$$

In order to have a complete solution both these equations must be satisfied. Another way of saying the same thing is that functions must be found such that when substituted in the left member of equation (26a) terms will be obtained corresponding to the terms of the right member, and that zero is a term of the right member even though it is not explicitly written.

It may be economical of effort to investigate what occurs when a trial solution is assumed in the form:

$$y = Be^{m\omega t} \,, \qquad (27)$$

where B is a constant, real or complex, and m is a complex number. The first two derivatives of equation (27) are:

$$\frac{dy}{d(\omega t)} = mBe^{m\omega t} \,, \qquad (28)$$

$$\frac{d^2y}{d(\omega t)^2} = m^2 Be^{m\omega t}$$

Upon substitution of equations (27) and (28) in the left member of equation (26a) or (26b), the left member becomes:

$$Be^{m\omega t}(\rho^2 m^2 + 2r\rho m + 1) \,. \qquad (29)$$

This expression may be made to equal zero by requiring that m satisfy:

$$\rho^2 m^2 + 2r\rho m + 1 = 0 , \qquad (30)$$

or that:

$$m = -\frac{r}{\rho} \pm j\frac{1}{\rho}\sqrt{1-r^2} = -\alpha \pm j\beta . \qquad (31)$$

Thus, if in equation (27), m is given either of the values shown in equation (31), then equation (27) becomes a solution of equation (26b). For all other values of m the parenthesis in expression (29) will have a value different from zero, which may be called $Z\angle\lambda$. Thus:

$$\rho^2 m^2 + 2r\rho m + 1 = Z\angle\lambda . \qquad (32)$$

If the conjugate of m or $\bar{m}$ is used in the left member of equation (32), the value obtained will be the conjugate of $Z\angle\lambda$, or $Z\angle-\lambda$.

The trial solution of equation (27) leads to the expression (29) for the left member of equation (26a). Expression (29), using the Z notation and $m = -\alpha + j\beta$, becomes:

$$Be^{mwt} \times Z\angle\lambda = Be^{-\alpha wt} \times e^{+jwt} \times Z\angle\lambda . \qquad (33)$$

If $\bar{m} = -\alpha - j\beta$ had been used in equation (27) in place of m, the result would have been:

$$Be^{\bar{m}wt} \times Z\angle-\lambda = Be^{-\alpha wt} \times e^{-jwt} \times Z\angle-\lambda . \qquad (34)$$

Now consider the trial solution with m and its conjugate $\bar{m}$ both present, or:

$$y = \tfrac{1}{2} B(e^{mwt} + e^{\bar{m}wt}) , \qquad (35a)$$

or

$$y = \tfrac{1}{2} Be^{-\alpha wt}(e^{+j\beta wt} + e^{-j\beta wt}) = Be^{-\alpha wt}\cos\beta wt . \qquad (35b)$$

From the discussion of expressions (33) and (34), the result of substitution in the left member of equation (26a) may be written directly by adding half of expression (33) and half of expression (34). The result is:

$$\tfrac{1}{2} Be^{-\alpha wt}\left\{e^{+j\beta wt} \times Z\angle\lambda + e^{-j\beta wt} \times Z\angle-\lambda\right\} . \qquad (36a)$$

Because $Z\angle\lambda$ and $Ze^{+j\lambda}$ are two notations for the same thing, it is evident that expression (36a) may be written:

$$\tfrac{1}{2} BZe^{-\alpha wt}\left\{e^{+j(\beta wt+\lambda)} + e^{-j(\beta wt+\lambda)}\right\} , \qquad (36b)$$

or $$B Z e^{-\alpha\omega t} \cos(b\omega t + \lambda), \qquad (36c)$$

or $$B(\angle\lambda)\, e^{-\alpha\omega t} \cos b\omega t, \qquad (36d)$$

The importance of what has been done since the introduction of equation (27) as a trial solution is that now one can pick a set of values of m and easily obtain the complete solution of equation (26a). For example, the choice of $m = 0$ causes the left member of equation (26a) to reduce to a constant, see expression (29). The choice of a real value of m causes reduction to a real exponential. The choice of a complex m and its conjugate causes reduction to a damped sinusoidal quantity. The omission of a real component for m and its conjugate causes reduction to an undamped sinusoidal quantity. Therefore the values of m which are needed for the solution of equation (26a) are the values which are shown in column 2 of Table I. The equation for y is:

$$y = B_0 e^{m_0 \omega t} + B_1 e^{m_1 \omega t} + \tfrac{1}{2} B_2 \{e^{m_2 \omega t} + e^{m_3 \omega t}\}$$
$$+ \tfrac{1}{2} B_3 \{e^{m_4 \omega t} + e^{m_5 \omega t}\} + \tfrac{1}{2} B_4 \{e^{m_6 \omega t} + e^{m_7 \omega t}\}, \qquad (37a)$$

or using the given values of m, Table I:

$$y = B_0 + B_1 e^{-2\frac{R}{L}\omega t} + B_2 e^{-\frac{R}{L}\omega t} \cos \omega t + B_3 \cos 2\omega t$$
$$+ B_4 e^{-\alpha\omega t} \cos \beta\omega t . \qquad (37b)$$

Equations or expressions (27), (29), (30), (31), (32), (35), and (36) permit writing by inspection the result of substituting any term in the left member of equation (26a). This substitution on the left side leads to distinctive terms which must be equal to the corresponding term of the right member of equation (26a). These equalities are:

$$\begin{aligned}
&B_0 && = \frac{E}{Z} \times \tfrac{1}{2} \\
&B_1 Z_1 \angle\Omega\, e^{-2\frac{R}{L}\omega t} && = \frac{E}{Z} \times e^{-2\frac{R}{L}\omega t} \\
&B_2 (Z_2 \angle\lambda_2) e^{-\frac{R}{L}\omega t} \cos \omega t && = \frac{E}{Z} [-\alpha e^{-\frac{R}{L}\omega t} \cos \omega t] \\
&B_3 (Z_3 \angle\lambda_3) \cos 2\omega t && = \frac{E}{Z} \times \tfrac{1}{4} \cos 2\omega t \qquad (38) \\
&B_4 (Z_4 \angle\lambda_4) e^{-\alpha\omega t} \cos \beta\omega t && = 0
\end{aligned}$$

and hence the B's have the values shown in Table I, except for B_4 which has yet to be determined because in equation (38), Z_4 is zero. A change in notation has been made for B_4 in Table I.

Using the B values of Table I and taking into account that the effect of λ in a B coefficient is to change the phase of a sinusoidal term, the general solution of equation (26a) may be written by revising equation (37b). The result is:

$$y = \frac{P}{K}\left\{\tfrac{1}{2} + \frac{1}{Z_1}e^{-\frac{R}{X}\omega t} - \frac{2}{Z_2}e^{-\frac{R}{X}\omega t}\cos(\omega t - \lambda_2) - \frac{1}{2Z_3}\cos(2\omega t - \lambda_3) - Ce^{-\alpha\omega t}\cos(\beta\omega t - \sigma)\right. \quad (39)$$

In order to satisfy the condition that the mass be initially at rest, it is necessary that:

$$\left.\begin{aligned} y &= 0 \\ \frac{dy}{d(\omega t)} &= 0 \end{aligned}\right\} \text{when } \omega t = 0 \quad (40)$$

This requires that the first derivative of equation (39) be obtained. The result is:

$$\frac{K}{P}\times\frac{dy}{d(\omega t)} = -2\frac{R}{X}\times\frac{1}{Z_1}e^{-\frac{R}{X}\omega t} - \frac{2}{Z_2}e^{-\frac{R}{X}\omega t}\left\{-\frac{R}{X}\cos(\omega t - \lambda_2) - \sin(\omega t - \lambda_2)\right\}$$
$$-\frac{1}{Z_3}\sin(2\omega t - \lambda_3) - Ce^{-\alpha\omega t}\left\{-\alpha\cos(\beta\omega t - \sigma) - \beta\sin(\beta\omega t - \sigma)\right\}. \quad (41)$$

For $\omega t = 0$, equations (39) and (41) reduce to:

$$\frac{K}{P}y = 0 = \tfrac{1}{2} + \frac{1}{Z_1} - \frac{2}{Z_2}\cos(-\lambda_2) + \frac{1}{2Z_3}\cos(-\lambda_3) - C\cos(-\sigma) \quad (42)$$

$$\frac{K}{P}\frac{dy}{d(\omega t)} = 0 = -2\frac{R}{X}\times\frac{1}{Z_1} + \frac{2}{Z_2}\left\{\frac{R}{X}\cos(-\lambda_2) + \sin(-\lambda_2)\right\}$$
$$-\frac{1}{Z_3}\sin(-\lambda_3) + C\left\{\alpha\cos(-\sigma) + \beta\sin(-\sigma)\right\}. \quad (43)$$

Equations (42) and (43) may be rewritten and used to compute C and σ in any given numerical case.

$$C\cos(-\sigma) = \tfrac{1}{2} + \frac{1}{Z_1} - \frac{2}{Z_2}\cos(-\lambda_2) + \frac{1}{2Z_3}\cos(-\lambda_3) \quad (42a)$$

$$C\left\{\alpha\cos(-\sigma) + \beta\sin(-\sigma)\right\} = +2\frac{R}{X}\times\frac{1}{Z_1} - \frac{2}{Z_2}\left\{\frac{R}{X}\cos(-\lambda_2) + \sin(-\lambda_2)\right\}$$
$$+\frac{1}{Z_3}\sin(-\lambda_3) \quad (43a)$$

Now a method of calculating results will be indicated. Start by selecting the value of R/X for the electrical circuit of interest, and also choose an appropriate fraction of critical damping of the mechanical structure. Since the m values all become definite numerical values, all items of interest become functions of ρ and ωt. Successive choices of ρ will permit curves to be drawn for the coefficients and phase angles. Start by evaluating $\Sigma \angle \lambda$ from expression (32). Refer to equation (39) to see how to employ these values for coefficients and phase angles. Use these values to calculate C and σ from equations (42a) and (43a). Equation (39) may now be written with numerical values except for y, $\frac{\rho}{K}$, and ωt. A few trial values of ωt will permit a maximum value for $K/\rho \times y$ to be obtained. Inspection of the whole calculation process shows that for the conventional method, where R/X and ρ are both taken as zero, the maximum value of $K/\rho \times y$ becomes $K/\rho \times 4$ and is designated y_{st}. Any requirement of a knowledge of the value of K/ρ can be dispensed with by taking the ratio of the y of equation (39) to y_{st} of the conventional method. A convenient expression of this ratio is:

$$4\frac{y}{y_{st}} = \frac{1}{2} + \frac{1}{\Sigma_1} e^{-\frac{\beta}{\alpha}\omega t} - \frac{2}{\Sigma_0} e^{-\frac{\beta}{\alpha}\omega t}\cos(\omega t - \lambda_0)$$

$$+\frac{1}{2\Sigma_2}\cos(2\omega t - \lambda_2) - Ce^{-\alpha\omega t}\cos(\beta\omega t - \sigma). \qquad (3)$$

The familiar routine of the conventional method may be used for calculation, and if the ratio of $(y_{max})/y_{st}$ is used as an additional factor, the result will be that indicated by the approximate theory given in this paper.

For some choices of constants and values of ρ, some of the terms involved in equation (3) may be dropped and others approximated and still the result may be of sufficient accuracy.

TABLE I

Values of m, Z, and B

Term No.	m	Designation of $Z \angle\Delta$	B
0	$0 + j0$	$Z_0 \angle\Delta_0 = 1.0$	$\frac{P}{K} \times \frac{1}{2}$
1	$-2\frac{R}{X} + j0$	$Z_1 \angle\Delta_1 = Z_1 \angle\Omega$	$\frac{P}{K} \times \frac{1}{Z_1}$
2	$-\frac{R}{X} + j1.0$	$Z_2 \angle\Delta_2$	$\frac{P}{K}\left[\frac{-2}{Z_1 \angle\Delta_2}\right] = \frac{P}{K}\left[\frac{-2}{Z_2} \angle -\Delta_2\right]$
3	$0 + j2.0$	$Z_3 \angle\Delta_3$	$\frac{P}{K} \times \frac{1}{2Z_3 \angle\Delta_3} = \frac{P}{K} \times \frac{1}{2Z_3} \angle -\Delta_3$
4	$-\alpha + j\beta$	$Z_4 \angle\Delta_4 = 0$	$\frac{P}{K}\left[-C \angle -\alpha\right]$